

Gauged baryon and lepton numbers in supersymmetry with a 125 GeV Higgs

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Abstract

Assuming that the Yukawa couplings between the Higgs and exotic quarks cannot be ignored, we analyze the signals of decay channels $h \rightarrow \gamma\gamma$ and $h \rightarrow VV^*$ ($V = Z, W$) with the Higgs mass around 125 GeV in a supersymmetric extension of the standard model where baryon and lepton numbers are local gauge symmetries. Adopting some assumptions on relevant parameter space, we can account for the experimental data on Higgs from ATLAS and CMS naturally.

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I. INTRODUCTION

The main destination of the Large Hadron Collider (LHC) is to understand the origin of the electroweak symmetry breaking, and searches the neutral Higgs predicted by the standard model (SM) and its various extensions. Recently, ATLAS and CMS have reported significant excess events which are interpreted probably to be related to the neutral Higgs with mass $m_{h_0} \sim 124 - 126$ GeV[1, 2]. This implies that the Higgs mechanism to break electroweak symmetry possibly has a solid experimental cornerstone.

As the simplest soft broken supersymmetry theory, the minimal supersymmetric extension of the standard model (MSSM) [3] has drawn the attention from physicist for a long time. Furthermore, Broken baryon number (B) can explain the origin of the matter-antimatter asymmetry in the Universe naturally. Since heavy majorana neutrinos contained in the seesaw mechanism can induce the tiny neutrino masses[4] to explain the neutrino oscillation experiment, lepton number (L) is also expected to be broken. Ignoring Yukawa couplings between Higgs doublets and exotic quarks, the authors of literature[5, 6] investigate the predictions for the mass and decays of the lightest CP-even Higgs in a minimal local gauged B and L supersymmetric extension of the SM which is named BLMSSM. Since the new quarks are vector-like, one obtains that their masses can be above 500 GeV without assuming large couplings to the Higgs doublets in this model. Therefore, there are no Landau poles for the Yukawa couplings here. Additionally, literature[7] also examines two extensions of the SM where B and L are spontaneously broken gauge symmetries around TeV scale. Assuming that the Yukawa couplings between Higgs and exotic quarks cannot be ignored here, we investigate the lightest CP-even Higgs decay channels $h \rightarrow \gamma\gamma$, $h \rightarrow VV^*$ ($V = Z, W$) in the BLMSSM.

Our presentation is organized as follows. In section II, we briefly summarize the main ingredients of the BLMSSM, then present the mass squared matrices for neutral scalar sectors and the mass matrices for exotic quarks, respectively. We discuss the corrections on the mass squared matrix of CP-even Higgs from exotic fields in section III, and present the decay widths for $h^0 \rightarrow \gamma\gamma$, VV^* ($V = Z, W$) in section IV. The numerical analyses are given in section V, and our conclusions are summarized in section VI.

II. A SUPERSYMMETRIC EXTENSION OF THE SM WHERE B AND L ARE LOCAL GAUGE SYMMETRIES

When B and L are local gauge symmetries, one can enlarge the local gauge group of the SM to $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$. In the supersymmetric extension of the SM proposed in Ref.[5, 6], the exotic superfields include the new quarks $\hat{Q}_4 \sim (3, 2, 1/6, B_4, 0)$, $\hat{U}_4^c \sim (\bar{3}, 1, -2/3, -B_4, 0)$, $\hat{D}_4^c \sim (\bar{3}, 1, 1/3, -B_4, 0)$, $\hat{Q}_5^c \sim (\bar{3}, 2, -1/6, -(1+B_4), 0)$, $\hat{U}_5 \sim (3, 1, 2/3, 1+B_4, 0)$, $\hat{D}_5 \sim (3, 1, -1/3, 1+B_4, 0)$, and the new leptons $\hat{L}_4 \sim (1, 2, -1/2, 0, L_4)$, $\hat{E}_4^c \sim (1, 1, 1, 0, -L_4)$, $\hat{N}_4^c \sim (1, 1, 0, 0, -L_4)$, $\hat{L}_5^c \sim (1, 2, 1/2, 0, -(3+L_4))$, $\hat{E}_5 \sim (1, 1, -1, 0, 3+L_4)$, $\hat{N}_5 \sim (1, 1, 0, 0, 3+L_4)$ to cancel the B and L anomalies. The 'brand new' Higgs superfields $\hat{\Phi}_B \sim (1, 1, 0, 1, 0)$ and $\hat{\varphi}_B \sim (1, 1, 0, -1, 0)$ acquire nonzero vacuum expectation values (VEVs) to break Baryon number spontaneously. Meanwhile, nonzero VEVs of Φ_B and ϕ_B also induce the large masses for exotic quarks. In addition, the superfields $\hat{\Phi}_L \sim (1, 1, 0, 0, -2)$ and $\hat{\varphi}_L \sim (1, 1, 0, 0, 2)$ acquire nonzero VEVs to break Lepton number spontaneously. In order to avoid stability for the exotic quarks, the model also includes the superfields $\hat{X} \sim (1, 1, 0, 2/3+B_4, 0)$, $\hat{X}' \sim (1, 1, 0, -(2/3+B_4), 0)$. Actually, the lightest one can be a dark matter candidate. The superpotential of the model is written as

$$\mathcal{W}_{BLMSSM} = \mathcal{W}_{MSSM} + \mathcal{W}_B + \mathcal{W}_L + \mathcal{W}_X, \quad (1)$$

where \mathcal{W}_{MSSM} is superpotential of the MSSM, and

$$\begin{aligned} \mathcal{W}_B &= \lambda_Q \hat{Q}_4 \hat{Q}_5^c \hat{\Phi}_B + \lambda_U \hat{U}_4^c \hat{U}_5 \hat{\varphi}_B + \lambda_D \hat{D}_4^c \hat{D}_5 \hat{\varphi}_B + \mu_B \hat{\Phi}_B \hat{\varphi}_B \\ &\quad + Y_{u_4} \hat{Q}_4 \hat{H}_u \hat{U}_4^c + Y_{d_4} \hat{Q}_4 \hat{H}_d \hat{D}_4^c + Y_{u_5} \hat{Q}_5^c \hat{H}_d \hat{U}_5 + Y_{d_5} \hat{Q}_5^c \hat{H}_u \hat{D}_5, \\ \mathcal{W}_L &= Y_{e_4} \hat{L}_4 \hat{H}_d \hat{E}_4^c + Y_{\nu_4} \hat{L}_4 \hat{H}_u \hat{N}_4^c + Y_{e_5} \hat{L}_5^c \hat{H}_u \hat{E}_5 + Y_{\nu_5} \hat{L}_5^c \hat{H}_d \hat{N}_5 \\ &\quad + Y_\nu \hat{L} \hat{H}_u \hat{N}^c + \lambda_{N^c} \hat{N}^c \hat{N}^c \hat{\varphi}_L + \mu_L \hat{\Phi}_L \hat{\varphi}_L, \\ \mathcal{W}_X &= \lambda_1 \hat{Q} \hat{Q}_5^c \hat{X} + \lambda_2 \hat{U}^c \hat{U}_5 \hat{X}' + \lambda_3 \hat{D}^c \hat{D}_5 \hat{X}' + \mu_X \hat{X} \hat{X}'. \end{aligned} \quad (2)$$

In the superpotential above, the exotic quarks obtain TeV scale masses after Φ_B , φ_B acquire nonzero VEVs, and the nonzero VEV of φ_L implements the seesaw mechanism for the tiny

neutrino masses. Correspondingly, the soft breaking terms are generally given as

$$\begin{aligned}
\mathcal{L}_{soft} = & \mathcal{L}_{soft}^{MSSM} - (m_{\tilde{N}^c}^2)_{IJ} \tilde{N}_I^{c*} \tilde{N}_J^c - m_{\tilde{Q}_4}^2 \tilde{Q}_4^\dagger \tilde{Q}_4 - m_{\tilde{U}_4}^2 \tilde{U}_4^{c*} \tilde{U}_4^c - m_{\tilde{D}_4}^2 \tilde{D}_4^{c*} \tilde{D}_4^c \\
& - m_{\tilde{Q}_5}^2 \tilde{Q}_5^{c\dagger} \tilde{Q}_5^c - m_{\tilde{U}_5}^2 \tilde{U}_5^{*} \tilde{U}_5 - m_{\tilde{D}_5}^2 \tilde{D}_5^{*} \tilde{D}_5 - m_{\tilde{L}_4}^2 \tilde{L}_4^\dagger \tilde{L}_4 - m_{\tilde{\nu}_4}^2 \tilde{\nu}_4^{c*} \tilde{\nu}_4^c \\
& - m_{\tilde{E}_4}^2 \tilde{e}_4^{c*} \tilde{e}_4^c - m_{\tilde{L}_5}^2 \tilde{L}_5^{c\dagger} \tilde{L}_5^c - m_{\tilde{\nu}_5}^2 \tilde{\nu}_5^{*} \tilde{\nu}_5 - m_{\tilde{E}_5}^2 \tilde{e}_5^{*} \tilde{e}_5 - m_{\Phi_B}^2 \Phi_B^* \Phi_B \\
& - m_{\varphi_B}^2 \varphi_B^* \varphi_B - m_{\Phi_L}^2 \Phi_L^* \Phi_L - m_{\varphi_L}^2 \varphi_L^* \varphi_L - \left(m_B \lambda_B \lambda_B + m_L \lambda_L \lambda_L + h.c. \right) \\
& + \left\{ A_{u_4} Y_{u_4} \tilde{Q}_4 H_u \tilde{U}_4^c + A_{d_4} Y_{d_4} \tilde{Q}_4 H_d \tilde{D}_4^c + A_{u_5} Y_{u_5} \tilde{Q}_5 H_u \tilde{U}_5^c + A_{d_5} Y_{d_5} \tilde{Q}_5 H_d \tilde{D}_5^c \right. \\
& + A_{BQ} \lambda_Q \tilde{Q}_4 \tilde{Q}_5^c \Phi_B + A_{BU} \lambda_U \tilde{U}_4^c \tilde{U}_5 \varphi_B + A_{BD} \lambda_D \tilde{D}_4^c \tilde{D}_5 \varphi_B + B_B \mu_B \Phi_B \varphi_B + h.c. \left. \right\} \\
& + \left\{ A_{e_4} Y_{e_4} \tilde{L}_4 H_d \tilde{E}_4^c + A_{N_4} Y_{N_4} \tilde{L}_4 H_u \tilde{N}_4^c + A_{e_5} Y_{e_5} \tilde{L}_5 H_u \tilde{E}_5^c + A_{N_5} Y_{N_5} \tilde{L}_5 H_d \tilde{N}_5^c \right. \\
& + A_N Y_N \tilde{L}_5 H_u \tilde{N}_5^c + A_{Nc} \lambda_{Nc} \tilde{N}^c \tilde{N}^c \varphi_L + B_L \mu_L \Phi_L \varphi_L + h.c. \left. \right\} \\
& + \left\{ A_1 \lambda_1 \tilde{Q} \tilde{Q}_5^c X + A_2 \lambda_2 \tilde{U}^c \tilde{U}_5 X' + A_3 \lambda_3 \tilde{D}^c \tilde{D}_5 X' + B_X \mu_X X X' + h.c. \right\}, \quad (3)
\end{aligned}$$

where $\mathcal{L}_{soft}^{MSSM}$ is soft breaking terms of the MSSM, λ_B , λ_L are gauginos of $U(1)_B$ and $U(1)_L$, respectively. After the $SU(2)_L$ doublets H_u , H_d and $SU(2)_L$ singlets Φ_B , φ_B , Φ_L , φ_L acquire the nonzero VEVs v_u , v_d , v_B , \bar{v}_B , and v_L , \bar{v}_L ,

$$\begin{aligned}
H_u &= \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}(v_u + H_u^0 + iP_u^0) \end{pmatrix}, \\
H_d &= \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + H_d^0 + iP_d^0) \\ H_d^- \end{pmatrix}, \\
\Phi_B &= \frac{1}{\sqrt{2}}(v_B + \Phi_B^0 + iP_B^0), \\
\varphi_B &= \frac{1}{\sqrt{2}}(\bar{v}_B + \varphi_B^0 + i\bar{P}_B^0), \\
\Phi_L &= \frac{1}{\sqrt{2}}(v_L + \Phi_L^0 + iP_L^0), \\
\varphi_L &= \frac{1}{\sqrt{2}}(\bar{v}_L + \varphi_L^0 + i\bar{P}_L^0), \quad (4)
\end{aligned}$$

the local gauge symmetry $SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$ is broken down to the electromagnetic symmetry $U(1)_e$, where

$$G^\pm = \cos \beta H_d^\pm + \sin \beta H_u^\pm \quad (5)$$

denotes the charged Goldstone boson, and

$$\begin{aligned}
G^0 &= \cos \beta P_d^0 + \sin \beta P_u^0, \\
G_B^0 &= \cos \beta_B P_B^0 + \sin \beta_B \overline{P}_B^0, \\
G_L^0 &= \cos \beta_L P_L^0 + \sin \beta_L \overline{P}_L^0
\end{aligned} \tag{6}$$

denote the neutral Goldstone bosons, respectively. Here $\tan \beta = v_u/v_d$, $\tan \beta_B = \overline{v}_B/v_B$, and $\tan \beta_L = \overline{v}_L/v_L$. Correspondingly, the physical neutral pseudoscalar fields are

$$\begin{aligned}
A^0 &= -\sin \beta P_d^0 + \cos \beta P_u^0, \\
A_B^0 &= -\sin \beta_B P_B^0 + \cos \beta_B \overline{P}_B^0, \\
A_L^0 &= -\sin \beta_L P_L^0 + \cos \beta_L \overline{P}_L^0.
\end{aligned} \tag{7}$$

At tree level, the masses for those particles are respectively formulated as

$$\begin{aligned}
m_{A^0}^2 &= \frac{B\mu}{\cos \beta \sin \beta}, \\
m_{A_B^0}^2 &= \frac{B_B \mu_B}{\cos \beta_B \sin \beta_B}, \\
m_{A_L^0}^2 &= \frac{B_L \mu_L}{\cos \beta_L \sin \beta_L}.
\end{aligned} \tag{8}$$

Meanwhile the charged Higgs is

$$H^\pm = -\sin \beta H_d^\pm + \cos \beta H_u^\pm \tag{9}$$

with the tree level mass squared

$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2. \tag{10}$$

In the two Higgs doublet sector, the mass squared matrix of neutral CP-even Higgs is diagonalized by the rotation

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H_d^0 \\ H_u^0 \end{pmatrix}, \tag{11}$$

where h^0 is the lightest neutral CP-even Higgs.

In the basis (Φ_B^0, φ_B^0) , the mass squared matrix is

$$\mathcal{M}_{EB}^2 = \begin{pmatrix} m_{Z_B}^2 \cos^2 \beta_B + m_{A_B^0}^2 \sin^2 \beta_B, & (m_{Z_B}^2 + m_{A_B^0}^2) \cos \beta_B \sin \beta_B \\ (m_{Z_B}^2 + m_{A_B^0}^2) \cos \beta_B \sin \beta_B, & m_{Z_B}^2 \sin^2 \beta_B + m_{A_B^0}^2 \cos^2 \beta_B \end{pmatrix}, \quad (12)$$

where $m_{Z_B}^2 = g_B^2(v_B^2 + \bar{v}_B^2)$ is mass squared of the neutral $U(1)_B$ gauge boson Z_B . Defining the mixing angle α_B through

$$\tan 2\alpha_B = \frac{m_{Z_B}^2 + m_{A_B^0}^2}{m_{Z_B}^2 - m_{A_B^0}^2} \tan 2\beta_B, \quad (13)$$

we obtain two mass eigenstates as

$$\begin{pmatrix} H_B^0 \\ h_B^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha_B & \sin \alpha_B \\ -\sin \alpha_B & \cos \alpha_B \end{pmatrix} \begin{pmatrix} \Phi_B^0 \\ \varphi_B^0 \end{pmatrix}. \quad (14)$$

Similarly the mass squared matrix for (Φ_L^0, φ_L^0) is written as

$$\mathcal{M}_{EL}^2 = \begin{pmatrix} m_{Z_L}^2 \cos^2 \beta_L + m_{A_L^0}^2 \sin^2 \beta_L, & (m_{Z_L}^2 + m_{A_L^0}^2) \cos \beta_L \sin \beta_L \\ (m_{Z_L}^2 + m_{A_L^0}^2) \cos \beta_L \sin \beta_L, & m_{Z_L}^2 \sin^2 \beta_L + m_{A_L^0}^2 \cos^2 \beta_L \end{pmatrix}, \quad (15)$$

with $m_{Z_L}^2 = 4g_L^2(v_L^2 + \bar{v}_L^2)$ denoting mass squared of the neutral $U(1)_L$ gauge boson Z_L .

In four-component Dirac spinors, the mass matrix for exotic quarks with charged 2/3 is

$$-\mathcal{L}_{t'}^{mass} = \begin{pmatrix} \bar{t}'_{4R}, & \bar{t}'_{5R} \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{u_5} v_d \\ -\frac{1}{\sqrt{2}}Y_{u_4} v_u, & \frac{1}{\sqrt{2}}\lambda_u \bar{v}_B \end{pmatrix} \begin{pmatrix} t'_{4L} \\ t'_{5L} \end{pmatrix} + h.c. \quad (16)$$

Using the unitary transformations

$$\begin{pmatrix} t'_{4L} \\ t'_{5L} \end{pmatrix} = U_{t'}^\dagger \cdot \begin{pmatrix} t_{4L} \\ t_{5L} \end{pmatrix}, \quad \begin{pmatrix} t'_{4R} \\ t'_{5R} \end{pmatrix} = W_{t'}^\dagger \cdot \begin{pmatrix} t_{4R} \\ t_{5R} \end{pmatrix}, \quad (17)$$

we diagonalize the mass matrix for the vector quarks with charged 2/3:

$$W_{t'}^\dagger \cdot \begin{pmatrix} \frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{u_5} v_d \\ -\frac{1}{\sqrt{2}}Y_{u_4} v_u, & \frac{1}{\sqrt{2}}\lambda_u \bar{v}_B \end{pmatrix} \cdot U_{t'} = \text{diag}(m_{t_4}, m_{t_5}) \quad (18)$$

Similarly we can write the mass matrix for the exotic quarks with charged -1/3 as

$$-\mathcal{L}_{b'}^{mass} = \begin{pmatrix} \bar{b}_{4R}, & \bar{b}_{5R} \end{pmatrix} \begin{pmatrix} -\frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{d_5} v_u \\ -\frac{1}{\sqrt{2}}Y_{d_4} v_d, & \frac{1}{\sqrt{2}}\lambda_d \bar{v}_B \end{pmatrix} \begin{pmatrix} b_{4L} \\ b_{5L} \end{pmatrix} + h.c. \quad (19)$$

Adopting the unitary transformations

$$\begin{pmatrix} b'_{4L} \\ b'_{5L} \end{pmatrix} = U_{b'}^\dagger \cdot \begin{pmatrix} b_{4L} \\ b_{5L} \end{pmatrix}, \quad \begin{pmatrix} b'_{4R} \\ b'_{5R} \end{pmatrix} = W_{b'}^\dagger \cdot \begin{pmatrix} b_{4R} \\ b_{5R} \end{pmatrix}, \quad (20)$$

one can diagonalize mass matrix for the vector quarks with charged $-1/3$ as

$$W_{b'}^\dagger \cdot \begin{pmatrix} -\frac{1}{\sqrt{2}}\lambda_Q v_B, & -\frac{1}{\sqrt{2}}Y_{d_5} v_u \\ -\frac{1}{\sqrt{2}}Y_{d_4} v_d, & \frac{1}{\sqrt{2}}\lambda_d \bar{v}_B \end{pmatrix} \cdot U_{b'} = \text{diag}(m_{b_4}, m_{b_5}). \quad (21)$$

Assuming CP conservation in exotic quark sector, we then derive the flavor conservative couplings between the lightest neutral CP-even Higgs and charged $2/3$ exotic quarks:

$$\mathcal{L}_{Ht't'} = \frac{1}{\sqrt{2}} \sum_{i=1}^2 \left[Y_{u_4} (W_t^T)_{i2} (U_t)_{1i} \cos \alpha + Y_{u_5} (W_t^T)_{i1} (U_t)_{2i} \sin \alpha \right] h^0 \bar{t}_{i+3} t_{i+3}, \quad (22)$$

where T represents the transposing transformation of a matrix. In a similar way, the flavor conservative couplings between the lightest neutral CP-even Higgs and charged $-1/3$ exotic quarks are written as

$$\mathcal{L}_{Hb'b'} = \frac{1}{\sqrt{2}} \sum_{i=1}^2 \left[Y_{d_4} (W_b^T)_{i2} (U_b)_{1i} \sin \alpha - Y_{d_5} (W_b^T)_{i1} (U_b)_{2i} \cos \alpha \right] h^0 \bar{b}_{i+3} b_{i+3}. \quad (23)$$

Using the superpotential in Eq.(1) and the soft breaking terms, we write the mass squared matrices for exotic scalar quarks as

$$-\mathcal{L}_{\widetilde{EQ}}^{mass} = \tilde{t}^\dagger \cdot \mathcal{M}_{t'}^2 \cdot \tilde{t}' + \tilde{b}^\dagger \cdot \mathcal{M}_{b'}^2 \cdot \tilde{b}' \quad (24)$$

with $\tilde{t}^T = (\tilde{Q}_4^1, \tilde{U}_4^{c*}, \tilde{Q}_5^{2c*}, \tilde{U}_5)$, $\tilde{b}^T = (\tilde{Q}_4^2, \tilde{D}_4^{c*}, \tilde{Q}_5^{1c*}, \tilde{D}_5^*)$. The concrete expressions for 4×4 mass squared matrices $\mathcal{M}_{t'}^2$, $\mathcal{M}_{b'}^2$ are given in appendix B, and the couplings between the lightest neutral CP-even Higgs and exotic scalar quarks are collected in appendix C.

III. THE LIGHTEST CP-EVEN HIGGS MASS

It is well known since quite some time that radiative corrections modify the tree level mass squared matrix of neutral Higgs substantially in the MSSM, where the main effect originates from one-loop diagrams involving the top quark and its scalar partners $\tilde{t}_{1,2}$ [8].

In order to obtain masses of the neutral CP-even Higgs reasonably, we should include the radiative corrections from exotic fermions and corresponding supersymmetric partners in the BLMSSM. Then, the mass squared matrix for the neutral CP-even Higgs in the basis (H_d^0, H_u^0) is written as

$$\mathcal{M}_{even}^2 = \begin{pmatrix} M_{11}^2 + \Delta_{11} & M_{12}^2 + \Delta_{12} \\ M_{12}^2 + \Delta_{12} & M_{22}^2 + \Delta_{22} \end{pmatrix}, \quad (25)$$

where

$$\begin{aligned} M_{11}^2 &= m_Z^2 \cos^2 \beta + m_{A^0}^2 \sin^2 \beta, \\ M_{12}^2 &= -(m_Z^2 + m_{A^0}^2) \sin \beta \cos \beta, \\ M_{22}^2 &= m_Z^2 \sin^2 \beta + m_{A^0}^2 \cos^2 \beta, \end{aligned} \quad (26)$$

and m_{A^0} denotes the pseudo-scalar Higgs mass at tree level. The radiative corrections originate from the MSSM sector, exotic fermions and corresponding scalar fermions respectively in this model:

$$\begin{aligned} \Delta_{11} &= \Delta_{11}^{MSSM} + \Delta_{11}^B + \Delta_{11}^L, \\ \Delta_{12} &= \Delta_{12}^{MSSM} + \Delta_{12}^B + \Delta_{12}^L, \\ \Delta_{22} &= \Delta_{22}^{MSSM} + \Delta_{22}^B + \Delta_{22}^L. \end{aligned} \quad (27)$$

Here the concrete expressions for Δ_{11}^{MSSM} , Δ_{12}^{MSSM} , Δ_{22}^{MSSM} at two-loop level can be found in literature[9], the one-loop radiative corrections from exotic quark fields are formulated as[10]

$$\begin{aligned} \Delta_{11}^B &= \frac{3G_F Y_{u_4}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu^2 (A_{u_4} - \mu \cot \beta)^2}{(m_{\tilde{t}'_1}^2 - m_{\tilde{t}'_2}^2)^2} g(m_{\tilde{t}'_1}, m_{\tilde{t}'_2}) \\ &+ \frac{3G_F Y_{u_5}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \left\{ \ln \frac{m_{\tilde{t}'_3} m_{\tilde{t}'_4}}{m_{\tilde{t}_5}^2} + \frac{A_{u_5} (A_{u_5} - \mu \tan \beta)}{m_{\tilde{t}'_3}^2 - m_{\tilde{t}'_4}^2} \ln \frac{m_{\tilde{t}'_3}^2}{m_{\tilde{t}'_4}^2} \right. \\ &\left. + \frac{A_{u_5}^2 (A_{u_5} - \mu \tan \beta)^2}{(m_{\tilde{t}'_3}^2 - m_{\tilde{t}'_4}^2)^2} g(m_{\tilde{t}'_3}, m_{\tilde{t}'_4}) \right\} \end{aligned}$$

$$\begin{aligned}
& + \frac{3G_F Y_{d_4}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \left\{ \ln \frac{m_{\bar{b}'_1} m_{\bar{b}'_2}}{m_{b_4}^2} + \frac{A_{d_4}(A_{d_4} - \mu \tan \beta)}{m_{\bar{b}'_1}^2 - m_{\bar{b}'_2}^2} \ln \frac{m_{\bar{b}'_1}^2}{m_{\bar{b}'_2}^2} \right. \\
& + \frac{A_{d_4}^2 (A_{d_4} - \mu \tan \beta)^2}{(m_{\bar{b}'_1}^2 - m_{\bar{b}'_2}^2)^2} g(m_{\bar{b}'_1}, m_{\bar{b}'_2}) \left. \right\} \\
& + \frac{3G_F Y_{d_5}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu^2 (A_{d_5} - \mu \cot \beta)^2}{(m_{\bar{b}'_3}^2 - m_{\bar{b}'_4}^2)^2} g(m_{\bar{b}'_3}, m_{\bar{b}'_4}) , \\
\Delta_{12}^B = & \frac{3G_F Y_{u_4}^4 v^4}{8\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu(-A_{u_4} + \mu \cot \beta)}{m_{\bar{t}'_1}^2 - m_{\bar{t}'_2}^2} \left\{ \ln \frac{m_{\bar{t}'_1}}{m_{\bar{t}'_2}} + \frac{A_{u_4}(A_{u_4} - \mu \cot \beta)}{m_{\bar{t}'_1}^2 - m_{\bar{t}'_2}^2} g(m_{\bar{t}'_1}, m_{\bar{t}'_2}) \right\} \\
& + \frac{3G_F Y_{u_5}^4 v^4}{8\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu(-A_{u_5} + \mu \tan \beta)}{m_{\bar{t}'_3}^2 - m_{\bar{t}'_4}^2} \left\{ \ln \frac{m_{\bar{t}'_3}}{m_{\bar{t}'_4}} + \frac{A_{u_5}(A_{u_5} - \mu \tan \beta)}{m_{\bar{t}'_3}^2 - m_{\bar{t}'_4}^2} g(m_{\bar{t}'_3}, m_{\bar{t}'_4}) \right\} \\
& + \frac{3G_F Y_{d_4}^4 v^4}{8\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu(-A_{d_4} + \mu \tan \beta)}{m_{\bar{d}'_1}^2 - m_{\bar{d}'_2}^2} \left\{ \ln \frac{m_{\bar{d}'_1}}{m_{\bar{d}'_2}} + \frac{A_{d_4}(A_{d_4} - \mu \tan \beta)}{m_{\bar{d}'_1}^2 - m_{\bar{d}'_2}^2} g(m_{\bar{d}'_1}, m_{\bar{d}'_2}) \right\} \\
& + \frac{3G_F Y_{d_5}^4 v^4}{8\sqrt{2}\pi^2 \sin^2 \beta} \cdot \frac{\mu(-A_{d_5} + \mu \cot \beta)}{m_{\bar{b}'_3}^2 - m_{\bar{b}'_4}^2} \left\{ \ln \frac{m_{\bar{b}'_3}}{m_{\bar{b}'_4}} + \frac{A_{d_5}(A_{d_5} - \mu \cot \beta)}{m_{\bar{b}'_3}^2 - m_{\bar{b}'_4}^2} g(m_{\bar{b}'_3}, m_{\bar{b}'_4}) \right\} , \\
\Delta_{22}^B = & \frac{3G_F Y_{u_4}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \left\{ \ln \frac{m_{\bar{t}'_1} m_{\bar{t}'_2}}{m_{t_4}^2} + \frac{A_{u_4}(A_{u_4} - \mu \cot \beta)}{m_{\bar{t}'_1}^2 - m_{\bar{t}'_2}^2} \ln \frac{m_{\bar{t}'_1}^2}{m_{\bar{t}'_2}^2} \right. \\
& + \frac{A_{u_4}^2 (A_{u_4} - \mu \cot \beta)^2}{(m_{\bar{t}'_1}^2 - m_{\bar{t}'_2}^2)^2} g(m_{\bar{t}'_1}, m_{\bar{t}'_2}) \left. \right\} \\
& + \frac{3G_F Y_{u_5}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu^2 (A_{u_5} - \mu \tan \beta)^2}{(m_{\bar{t}'_3}^2 - m_{\bar{t}'_4}^2)^2} g(m_{\bar{t}'_3}, m_{\bar{t}'_4}) \\
& + \frac{3G_F Y_{d_4}^4 v^4}{4\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu^2 (A_{d_4} - \mu \tan \beta)^2}{(m_{\bar{b}'_1}^2 - m_{\bar{b}'_2}^2)^2} g(m_{\bar{b}'_1}, m_{\bar{b}'_2}) \\
& + \frac{3G_F Y_{d_5}^4 v^4}{4\sqrt{2}\pi^2 \sin^2 \beta} \left\{ \ln \frac{m_{\bar{b}'_3} m_{\bar{b}'_4}}{m_{b_5}^2} + \frac{A_{d_5}(A_{d_5} - \mu \cot \beta)}{m_{\bar{b}'_3}^2 - m_{\bar{b}'_4}^2} \ln \frac{m_{\bar{b}'_3}^2}{m_{\bar{b}'_4}^2} \right. \\
& + \frac{A_{d_5}^2 (A_{d_5} - \mu \cot \beta)^2}{(m_{\bar{b}'_3}^2 - m_{\bar{b}'_4}^2)^2} g(m_{\bar{b}'_3}, m_{\bar{b}'_4}) \left. \right\} , \tag{28}
\end{aligned}$$

here $v = \sqrt{v_u^2 + v_d^2} \simeq 246$ GeV and

$$g(x, y) = 1 - \frac{x^2 + y^2}{x^2 - y^2} \ln \frac{x}{y} . \tag{29}$$

To derive the results presented in Eq.(28), we adopt the assumption $|\lambda_Q v_B|, |\lambda_u \bar{v}_B|, |\lambda_d \bar{v}_B| \gg |Y_{u_4} v|, |Y_{u_5} v|, |Y_{d_4} v|, |Y_{d_5} v|$ in our calculation. Similarly, one can obtain the one-loop radiative corrections from exotic lepton fields presented in appendix D.

One most stringent constraint on parameter space of the BLMSSM is that the mass squared matrix in Eq.(25) should produce an eigenvalue around $(125 \text{ GeV})^2$ as mass squared of the lightest neutral CP-even Higgs. The current combination of the ATLAS and CMS data gives[1, 2, 11]:

$$m_{h^0} = 125.9 \pm 2.1 \text{ GeV} , \quad (30)$$

this fact constrains parameter space of the BLMSSM strongly.

IV. $gg \rightarrow h^0$ AND $h^0 \rightarrow \gamma\gamma, ZZ^*, WW^*$

The Higgs is produced chiefly through the gluon fusion at the LHC. In the SM, the leading order (LO) contributions originate from the one loop diagram which involves virtual top quarks. The cross section for this process is known to the next-to-next-to-leading order (NNLO)[12] which can enhance the LO result by 80-100%. Furthermore, any new particle which strongly couples with the Higgs can significantly modified this cross section. In supersymmetric extension of the SM considered here, the LO decay width for the process $h^0 \rightarrow gg$ is given by (see Ref.[13] and references therein)

$$\Gamma_{NP}(h^0 \rightarrow gg) = \frac{G_F \alpha_s^2 m_{h^0}^3}{64\sqrt{2}\pi^3} \left| \sum_q g_{h^0 qq} A_{1/2}(x_q) + \sum_{\tilde{q}} g_{h^0 \tilde{q}\tilde{q}} \frac{m_Z^2}{m_{\tilde{q}}^2} A_0(x_{\tilde{q}}) \right|^2 , \quad (31)$$

with $x_a = m_a^2/(4m_a^2)$. In addition, $q = t, b, t_4, t_5, b_4, b_5$ and $\tilde{q} = \tilde{t}_{1,2}, \tilde{b}_{1,2}, \tilde{U}_i, \tilde{D}_i$ ($i = 1, 2, 3, 4$). The concrete expressions for $g_{h^0 tt}, g_{h^0 bb}, g_{h^0 \tilde{t}_i \tilde{t}_i}, g_{h^0 \tilde{b}_i \tilde{b}_i}$, ($i = 1, 2$) can be found in literature[6], and

$$g_{h^0 t_4 t_4} = -\frac{\sqrt{2}m_W s_W}{em_{t_4}} \left[Y_{u_4} (W_t^T)_{12} (U_t)_{11} \cos \alpha + Y_{u_5} (W_t^T)_{11} (U_t)_{21} \sin \alpha \right] ,$$

$$g_{h^0 t_5 t_5} = -\frac{\sqrt{2}m_W s_W}{em_{t_5}} \left[Y_{u_4} (W_t^T)_{22} (U_t)_{12} \cos \alpha + Y_{u_5} (W_t^T)_{21} (U_t)_{22} \sin \alpha \right] ,$$

$$\begin{aligned}
g_{h^0 b_4 b_4} &= -\frac{\sqrt{2}m_W s_W}{em_{b_4}} \left[Y_{d_4}(W_b^T)_{12}(U_b)_{11} \sin \alpha - Y_{d_5}(W_b^T)_{11}(U_b)_{21} \cos \alpha \right], \\
g_{h^0 b_5 b_5} &= -\frac{\sqrt{2}m_W s_W}{em_{b_5}} \left[Y_{d_4}(W_b^T)_{22}(U_b)_{12} \sin \alpha - Y_{d_5}(W_b^T)_{21}(U_b)_{22} \cos \alpha \right], \\
g_{h^0 \tilde{u}_i \tilde{u}_i} &= -\frac{m_W^2 s_W}{em_{\tilde{u}_i}^2} \left[\xi_{uii}^S \cos \alpha - \xi_{dii}^S \sin \alpha \right], \quad (i = 1, 2, 3, 4), \\
g_{h^0 \tilde{D}_i \tilde{D}_i} &= -\frac{m_W^2 s_W}{em_{\tilde{D}_i}^2} \left[\eta_{uii}^S \cos \alpha - \eta_{dii}^S \sin \alpha \right], \quad (i = 1, 2, 3, 4).
\end{aligned} \tag{32}$$

Here, we adopt the abbreviation $s_W = \sin \theta_W$ with θ_W denoting the Weinberg angle. Furthermore, e is the electromagnetic coupling constant, and the concrete expressions of ξ_{uii}^S , ξ_{dii}^S , η_{uii}^S , η_{dii}^S can be found in appendix C. The form factors $A_{1/2}$, A_0 in Eq.(31) are defined as

$$\begin{aligned}
A_{1/2}(x) &= 2[x + (x-1)g(x)]/x^2, \\
A_0(x) &= -(x - g(x))/x^2,
\end{aligned} \tag{33}$$

with

$$g(x) = \begin{cases} \arcsin^2 \sqrt{x}, & x \leq 1 \\ -\frac{1}{4} \left[\ln \frac{1+\sqrt{1-1/x}}{1-\sqrt{1-1/x}} - i\pi \right]^2, & x > 1. \end{cases} \tag{34}$$

The Higgs to diphoton decay is also obtained from loop diagrams, the LO contributions are derived from the one loop diagrams containing virtual charged gauge boson W^\pm or virtual top quarks in the SM. In the BLMSSM, the exotic fermions $t_{4,5}$, $b_{4,5}$, $e_{4,5}$ together with their supersymmetric partners contribute the corrections to the decay width of Higgs to diphoton at LO, the corresponding expression is written as

$$\begin{aligned}
\Gamma_{NP}(h^0 \rightarrow \gamma\gamma) &= \frac{G_F \alpha^2 m_{h^0}^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 g_{h^0 ff} A_{1/2}(x_f) + g_{h^0 WW} A_1(x_W) \right. \\
&\quad + g_{h^0 H^+ H^-} \frac{m_W^2}{m_{H^\pm}^2} A_0(x_{H^\pm}) + \sum_{i=1}^2 g_{h^0 \chi_i^+ \chi_i^-} \frac{m_W}{m_{\chi_i}} A_{1/2}(x_{\chi_i}) \\
&\quad \left. + \sum_{\tilde{f}} N_c Q_{\tilde{f}}^2 g_{h^0 \tilde{f} \tilde{f}} \frac{m_{\tilde{f}}^2}{m_{\tilde{f}}^2} A_0(x_{\tilde{f}}) \right|^2,
\end{aligned} \tag{35}$$

where $g_{h^0 WW} = \sin(\beta - \alpha)$, the concrete expression for the loop functions A_1 is

$$A_1(x) = -\left[2x^2 + 3x + 3(2x - 1)g(x)\right]/x^2. \quad (36)$$

The concrete expressions for $g_{h^0 \chi_i^+ \chi_i^-}$, $g_{h^0 H^+ H^-}$ and the couplings between the lightest neutral CP-even Higgs and exotic leptons/sleptons can also be found in literature[6].

For the lightest neutral CP-even Higgs around 125 GeV mass, it can decay through the modes $h^0 \rightarrow ZZ^*$, $h^0 \rightarrow WW^*$ where Z^*/W^* denotes the off-shell neutral/charged electroweak gauge bosons. Summing over all channels available to the W^* or Z^* , one can write the widths as[14, 15]

$$\begin{aligned} \Gamma(h^0 \rightarrow WW^*) &= \frac{3e^4 m_{h^0}}{512\pi^3 s_W^4} |g_{h^0 WW}|^2 F\left(\frac{m_W}{m_{h^0}}\right), \\ \Gamma(h^0 \rightarrow ZZ^*) &= \frac{e^4 m_{h^0}}{2048\pi^3 s_W^4 c_W^4} |g_{h^0 ZZ}|^2 \left(7 - \frac{40}{3}s_W^2 + \frac{160}{9}s_W^4\right) F\left(\frac{m_Z}{m_{h^0}}\right), \end{aligned} \quad (37)$$

with $g_{h^0 ZZ} = g_{h^0 WW}$ and the abbreviation $c_W = \cos \theta_W$. The form factor $F(x)$ is given as

$$\begin{aligned} F(x) &= -(1 - x^2) \left(\frac{47}{2}x^2 - \frac{13}{2} + \frac{1}{x^2} \right) - 3(1 - 6x^2 + 4x^4) \ln x \\ &\quad + \frac{3(1 - 8x^2 + 20x^4)}{\sqrt{4x^2 - 1}} \cos^{-1} \left(\frac{3x^2 - 1}{2x^3} \right). \end{aligned} \quad (38)$$

Besides the Higgs discovery the ATLAS and CMS experiments have both observed an excess in Higgs production and decay into diphoton channel which is a factor $1.4 \sim 2$ times larger than the SM expectations. The observed signals for the diphoton and ZZ^* , WW^* channels are quantified by the ratios

$$\begin{aligned} R_{\gamma\gamma} &= \frac{\Gamma_{NP}(h_0 \rightarrow gg)\Gamma_{NP}(h_0 \rightarrow \gamma\gamma)}{\Gamma_{SM}(h_0 \rightarrow gg)\Gamma_{SM}(h_0 \rightarrow \gamma\gamma)}, \\ R_{VV^*} &= \frac{\Gamma_{NP}(h_0 \rightarrow gg)\Gamma_{NP}(h_0 \rightarrow VV^*)}{\Gamma_{SM}(h_0 \rightarrow gg)\Gamma_{SM}(h_0 \rightarrow VV^*)}, \quad (V = Z, W). \end{aligned} \quad (39)$$

The current values of the ratios are [1, 2, 11]:

$$\begin{aligned} \text{ATLAS} + \text{CMS} : \quad R_{\gamma\gamma} &= 1.77 \pm 0.33 , \\ \text{ATLAS} + \text{CMS} : \quad R_{VV^*} &= 0.94 \pm 0.40 , (V = Z, W) . \end{aligned} \quad (40)$$

Note that the combinations of the ATLAS and CMS results are taken from Ref.[11].

V. NUMERICAL ANALYSES

As mentioned above, the most stringent constraint on the parameter space is that the 2×2 mass squared matrix in Eq.(25) should predict the lightest eigenvector with a mass $m_{h_0} \simeq 125.9$ GeV. In order to obtain the final results coinciding with this condition, we require the tree level mass of CP-odd Higgs m_{A^0} satisfying

$$m_{A^0}^2 = \frac{m_{h_0}^2 (m_z^2 - m_{h_0}^2 + \Delta_{11} + \Delta_{22}) - m_z^2 \Delta_A + \Delta_{12}^2 - \Delta_{11} \Delta_{22}}{-m_{h_0}^2 + m_z^2 \cos^2 2\beta + \Delta_B} , \quad (41)$$

where

$$\begin{aligned} \Delta_A &= \sin^2 \beta \Delta_{11} + \cos^2 \beta \Delta_{22} + \sin 2\beta \Delta_{12} , \\ \Delta_B &= \cos^2 \beta \Delta_{11} + \sin^2 \beta \Delta_{22} + \sin 2\beta \Delta_{12} . \end{aligned} \quad (42)$$

Through scanning the parameter space, we find the evaluations on $R_{\gamma\gamma}$, R_{VV^*} and masses of the heaviest CP-even Higgs and CP-odd Higgs depending on $\tan \beta$ acutely as $m_{h_0} = 125.9$ GeV. In our numerical analysis, we adopt the ansatz on relevant parameter space

$$\begin{aligned} B_4 &= L_4 = \frac{3}{2} , \\ m_{\tilde{Q}_3} &= m_{\tilde{U}_3} = m_{\tilde{D}_3} = 1 \text{ TeV} , \\ m_{\tilde{U}_4} &= m_{\tilde{D}_4} = m_{\tilde{Q}_5} = m_{\tilde{U}_5} = m_{\tilde{D}_5} = 1 \text{ TeV} , \\ m_{\tilde{L}_4} &= m_{\tilde{\nu}_4} = m_{\tilde{E}_4} = m_{\tilde{L}_5} = m_{\tilde{\nu}_5} = m_{\tilde{E}_5} = 1 \text{ TeV} , \\ m_{Z_B} &= m_{Z_L} = 1 \text{ TeV} , \end{aligned}$$

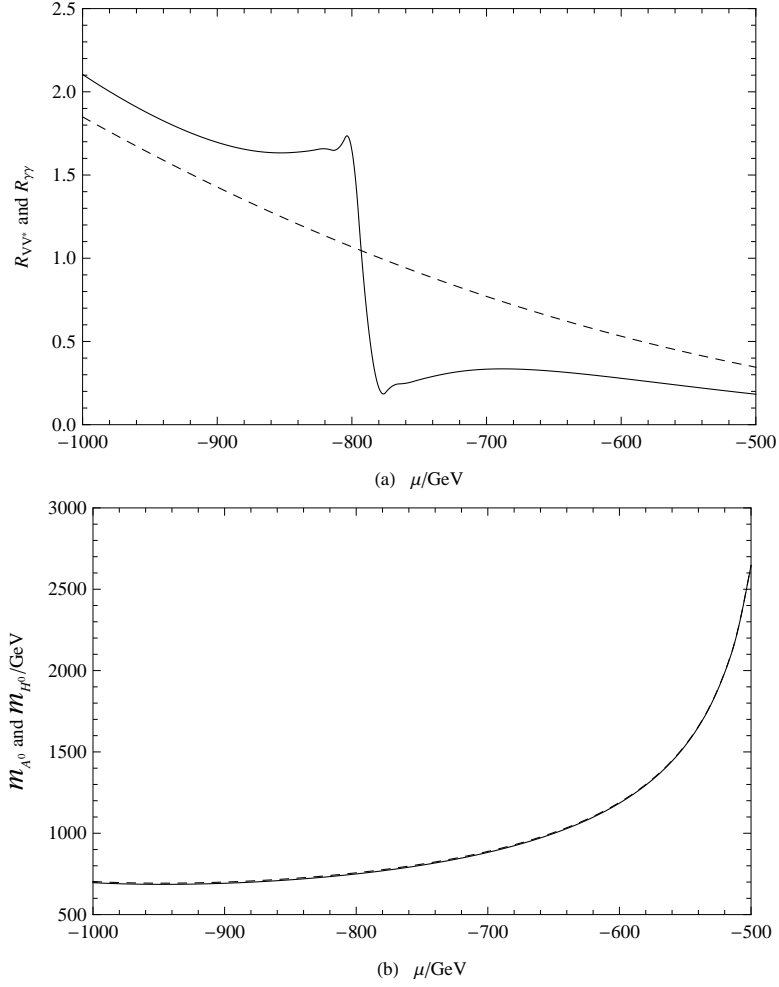


FIG. 1: As $Y_{u_5} = 0.7Y_b$, $Y_{d_5} = 0.13Y_t$, $m_{\tilde{Q}_4} = 790$ GeV and $A_t = -1$ TeV, (a) $R_{\gamma\gamma}$ (solid-line) and R_{VV^*} (dashed-line) vary with the parameter μ , and (b) m_{A^0} (solid-line) and m_{H^0} (dashed-line) vary with the parameter μ , respectively.

$$\begin{aligned}
A_{\nu_4} &= A_{e_4} = A_{\nu_5} = A_{e_4} = A_{d_4} = A_{u_5} = A_{d_5} = 550 \text{ GeV} , \\
v_{B_t} &= \sqrt{v_B^2 + \overline{v}_B^2} = 3 \text{ TeV} , \quad v_{L_t} = \sqrt{v_L^2 + \overline{v}_L^2} = 3 \text{ TeV} , \\
A_{BQ} &= A_{BU} = A_{BD} = -A_b = 1 \text{ TeV} , \\
Y_{u_4} &= 0.76 Y_t , \quad Y_{d_4} = 0.7 Y_b , \quad \lambda_Q = \lambda_u = \lambda_d = 0.5 \\
m_2 &= 750 \text{ GeV} , \quad \mu_B = 500 \text{ GeV} , \\
\tan \beta &= \tan \beta_B = \tan \beta_L = 2 ,
\end{aligned}$$

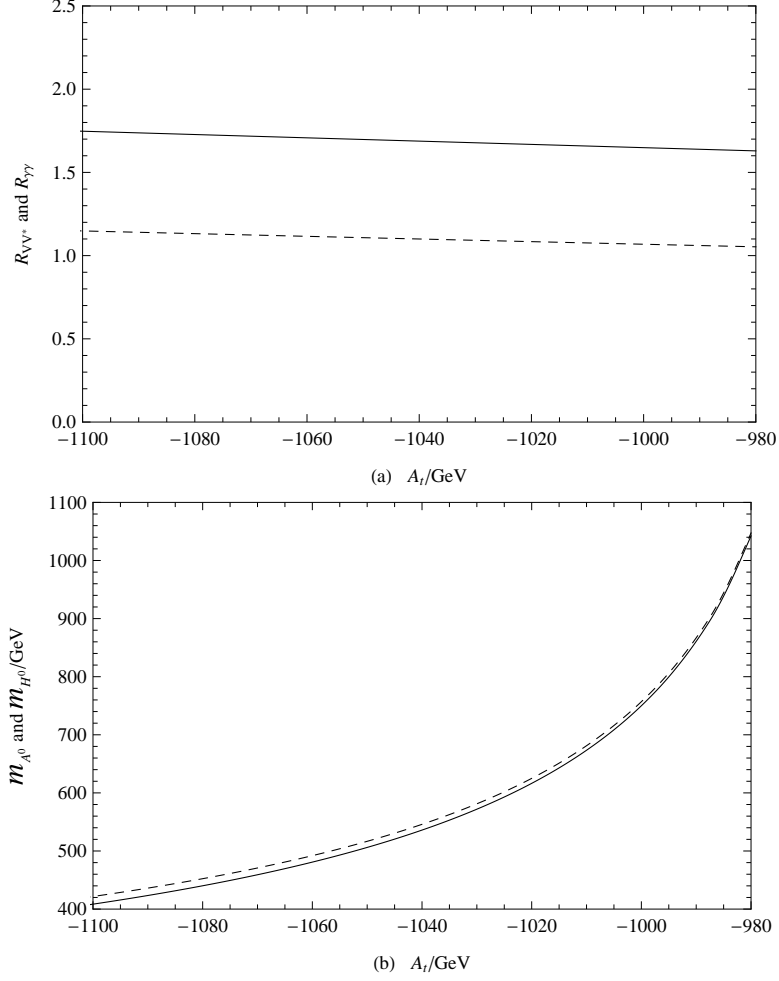


FIG. 2: As $Y_{u_5} = 0.7Y_b$, $Y_{d_5} = 0.13Y_t$, $m_{\tilde{Q}_4} = 790$ GeV and $\mu = -800$ GeV, (a) $R_{\gamma\gamma}$ (solid-line) and R_{VV^*} (dashed-line) vary with the parameter A_t , and (b) m_{A^0} (solid-line) and m_{H^0} (dashed-line) vary with the parameter A_t , respectively.

(43)

to reduce the number of free parameters in the model considered here. Furthermore, we choose the masses for exotic leptons from Ref.[6]:

$$m_{\nu_4} = m_{\nu_5} = 90 \text{ GeV} , \quad m_{e_4} = m_{e_5} = 100 \text{ GeV} . \quad (44)$$

For relevant parameters in the SM, we choose[16]

$$\alpha_s(m_Z) = 0.118 , \quad \alpha(m_Z) = 1/128 , \quad s_w^2(m_Z) = 0.23 ,$$

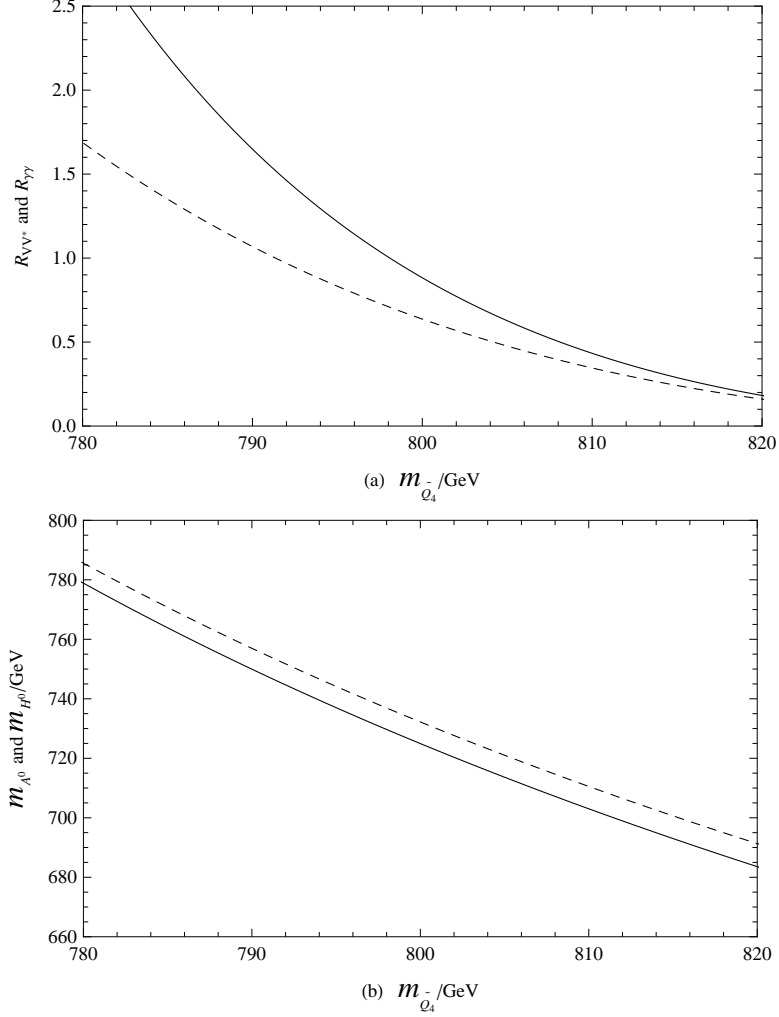


FIG. 3: As $Y_{u_5} = 0.7Y_b$, $Y_{d_5} = 0.13Y_t$, $A_t = -1$ TeV and $\mu = -800$ GeV, (a) $R_{\gamma\gamma}$ (solid-line) and R_{VV^*} (dashed-line) vary with the parameter $m_{\tilde{Q}_4}$, and (b) m_{A^0} (solid-line) and m_{H^0} (dashed-line) vary with the parameter $m_{\tilde{Q}_4}$, respectively.

$$m_t = 174.2 \text{ GeV} , \quad m_b = 4.2 \text{ GeV} , \quad m_W = 80.4 \text{ GeV} . \quad (45)$$

Considering that the CMS collaboration has excluded a SM Higgs with mass in the range $127.5 \text{ GeV} - 600 \text{ GeV}$, we require the theoretical evaluations on masses of the heaviest CP-even Higgs and CP-odd Higgs respectively in the range $m_{A^0} \geq 600 \text{ GeV}$, $m_{H^0} \geq 600 \text{ GeV}$. Choosing $Y_{u_5} = Y_{d_4} = 0.7Y_b$, $Y_{d_5} = 0.13Y_t$, $m_{\tilde{Q}_4} = 790 \text{ GeV}$ and $A_t = -1 \text{ TeV}$, we plot $R_{\gamma\gamma}$ (solid-line) and R_{VV^*} (dashed-line) varying with the parameter μ in Fig.1(a), and plot m_{A^0}

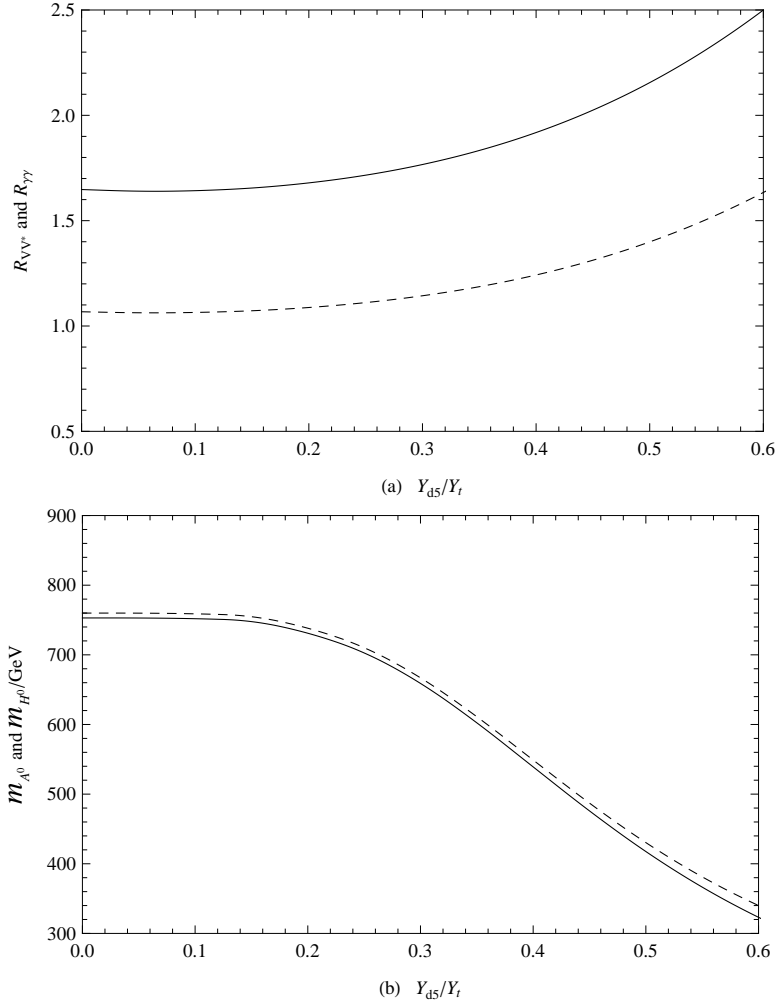


FIG. 4: As $Y_{u5} = 0.7Y_b$, $A_t = -1$ TeV and $\mu = -790$ GeV, (a) $R_{\gamma\gamma}$ (solid-line) and R_{VV^*} (dashed-line) vary with the ratio Y_{d5}/Y_t , and (b) m_{A^0} (solid-line) and m_{H^0} (dashed-line) vary with the ratio Y_{d5}/Y_t , respectively.

(solid-line) and m_{H^0} (dashed-line) varying with the parameter μ in Fig.1(b), respectively. Using our assumptions on relevant parameter space in the BLMSSM, we find the theoretical evaluations on $R_{\gamma\gamma}$, R_{VV^*} , m_{A^0} and m_{H^0} depending on μ acutely. As $-900 \text{ GeV} \leq \mu \leq -800 \text{ GeV}$, the theoretical predictions on $R_{\gamma\gamma}$ and R_{VV^*} are all coincide with experimental data in Eq.(40), and masses of the heaviest CP-even Higgs and CP-odd Higgs $m_{A^0} \sim m_{H^0} \geq 700 \text{ GeV}$ simultaneously.

Another parameter A_t maybe affects the theoretical evaluations on $R_{\gamma\gamma}$ and R_{VV^*} strongly here. Taking $Y_{u_5} = Y_{d_4} = 0.7Y_b$, $Y_{d_5} = 0.13Y_t$, $m_{\tilde{Q}_4} = 790$ GeV and $\mu = -800$ GeV, we depict $R_{\gamma\gamma}$ (solid-line) and R_{VV^*} (dashed-line) varying with the parameter A_t in Fig.2(a), and plot m_{A^0} (solid-line) and m_{H^0} (dashed-line) varying with the parameter A_t in Fig.2(b), respectively. Under our assumptions on the parameter space, the dependence of $R_{\gamma\gamma}$ and R_{VV^*} on A_t is very mild. Nevertheless, the theoretical evaluations of m_{A^0} and m_{H^0} depend on A_t strongly. When $A_t \geq -1$ TeV, the theoretical evaluations on $R_{\gamma\gamma}$ and R_{VV^*} are all coincide with experimental data in Eq.(40), and masses of the heaviest CP-even Higgs and CP-odd Higgs $m_{A^0} \sim m_{H^0} \geq 700$ GeV meantime.

Besides those parameters existing in the MSSM already, the 'brand new' parameters in the BLMSSM also affect the theoretical evaluations on $R_{\gamma\gamma}$, R_{VV^*} and m_{A^0} , m_{H^0} strongly as $m_{h^0} = 125.9$ GeV. In Fig.(3), we investigate $R_{\gamma\gamma}$, R_{VV^*} and m_{A^0} , m_{H^0} versus the soft mass of fourth generation left-handed scalar quarks $m_{\tilde{Q}_4}$. Where the solid line in Fig.(3)(a) represents $R_{\gamma\gamma}$ varying with $m_{\tilde{Q}_4}$, the dashed line in Fig.(3)(a) represents R_{VV^*} varying with $m_{\tilde{Q}_4}$, the solid line in Fig.(3)(b) represents m_{A^0} varying with $m_{\tilde{Q}_4}$, the dashed line in Fig.(3)(b) represents m_{H^0} varying with $m_{\tilde{Q}_4}$, respectively. Actually, the theoretical evaluations on $R_{\gamma\gamma}$, R_{VV^*} , m_{A^0} and m_{H^0} decrease steeply with the increasing of $m_{\tilde{Q}_4}$. When $m_{\tilde{Q}_4} \geq 800$ GeV, the theoretical prediction on $R_{\gamma\gamma}$ already lies out the experimental range in Eq.(40). In Fig.(4), we investigate the theoretical predictions on $R_{\gamma\gamma}$, R_{VV^*} and m_{A^0} , m_{H^0} versus the Yukawa coupling of fifth generation down-type quark Y_{d_5} . Where the solid line in Fig.(4)(a) represents $R_{\gamma\gamma}$ varying with Y_{d_5} , the dashed line in Fig.(4)(a) represents R_{VV^*} varying with Y_{d_5} , the solid line in Fig.(4)(b) represents m_{A^0} varying with Y_{d_5} , the dashed line in Fig.(4)(b) represents m_{H^0} varying with Y_{d_5} , respectively. In fact, the theoretical evaluations on $R_{\gamma\gamma}$ and R_{VV^*} raise slowly with increasing of the ratio Y_{d_5}/Y_t . When $Y_{d_5}/Y_t \geq 0.5$, the theoretical predictions on $R_{\gamma\gamma}$, R_{VV^*} exceed the experimental range in Eq.(40), and the numerical evaluations on m_{A^0} , m_{H^0} are below 600 GeV.

VI. SUMMARY

In framework of the BLMSSM, we attempt to account for the experimental data on Higgs reported by ATLAS and CMS recently. Assuming the Yukawa couplings between Higgs doublets and exotic quarks satisfying $Y_{u_4}, Y_{d_5} < Y_t$ as well as $Y_{d_4}, Y_{u_5} < Y_b$, we find the theoretical predictions on $R_{\gamma\gamma}, R_{VV^*}$ fitting the experimental data in Eq.(40) very well when $m_{h_0} = 125.9$ GeV. Furthermore, the numerical evaluations on m_{A^0}, m_{H^0} exceed 600 GeV simultaneously in some parameter space of the BLMSSM.

Acknowledgments

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Appendix A: The couplings between neutral Higgs and exotic quarks

In the mass basis, the couplings between the neutral Higgs and charged 2/3 exotic quarks are written as

$$\begin{aligned}
\mathcal{L}_{Ht't'} = & \frac{1}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[Y_{u_4}(W_t^\dagger)_{i2}(U_t)_{1j} \cos \alpha + Y_{u_5}(W_t^\dagger)_{i1}(U_t)_{2j} \sin \alpha \right] h^0 \bar{t}_{i+3} P_L t_{j+3} \right. \\
& + \left[Y_{u_4}(U_t^\dagger)_{i1}(W_t)_{2j} \cos \alpha + Y_{u_5}(U_t^\dagger)_{i2}(W_t)_{1j} \sin \alpha \right] h^0 \bar{t}_{i+3} P_R t_{j+3} \\
& + \left[Y_{u_4}(W_t^\dagger)_{i2}(U_t)_{1j} \sin \alpha - Y_{u_5}(W_t^\dagger)_{i1}(U_t)_{2j} \cos \alpha \right] H^0 \bar{t}_{i+3} P_L t_{j+3} \\
& + \left. \left[Y_{u_4}(U_t^\dagger)_{i1}(W_t)_{2j} \sin \alpha - Y_{u_5}(U_t^\dagger)_{i2}(W_t)_{1j} \cos \alpha \right] H^0 \bar{t}_{i+3} P_R t_{j+3} \right\} \\
& + \frac{i}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[Y_{u_4}(W_t^\dagger)_{i2}(U_t)_{1j} \cos \beta + Y_{u_5}(W_t^\dagger)_{i1}(U_t)_{2j} \sin \beta \right] A^0 \bar{t}_{i+3} P_L t_{j+3} \right. \\
& - \left[Y_{u_4}(U_t^\dagger)_{i1}(W_t)_{2j} \cos \beta + Y_{u_5}(U_t^\dagger)_{i2}(W_t)_{1j} \sin \beta \right] A^0 \bar{t}_{i+3} P_R t_{j+3} \\
& + \left[Y_{u_4}(W_t^\dagger)_{i2}(U_t)_{1j} \sin \beta - Y_{u_5}(W_t^\dagger)_{i1}(U_t)_{2j} \cos \beta \right] G^0 \bar{t}_{i+3} P_L t_{j+3} \\
& - \left. \left[Y_{u_4}(U_t^\dagger)_{i1}(W_t)_{2j} \sin \beta - Y_{u_5}(U_t^\dagger)_{i2}(W_t)_{1j} \cos \beta \right] G^0 \bar{t}_{i+3} P_R t_{j+3} \right\} \\
& - \frac{1}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[\lambda_u(W_t^\dagger)_{i2}(U_t)_{2j} \cos \alpha_B - \lambda_Q(W_t^\dagger)_{i1}(U_t)_{1j} \sin \alpha_B \right] h_B^0 \bar{t}_{i+3} P_L t_{j+3} \right.
\end{aligned}$$

$$\begin{aligned}
& + \left[\lambda_u (U_t^\dagger)_{i2} (W_t)_{2j} \cos \alpha_B - \lambda_Q (U_t^\dagger)_{i2} (W_t)_{2j} \sin \alpha_B \right] h_B^0 \bar{t}_{i+3} P_R t_{j+3} \\
& + \left[\lambda_u (W_t^\dagger)_{i2} (U_t)_{2j} \sin \alpha_B + \lambda_Q (W_t^\dagger)_{i1} (U_t)_{1j} \cos \alpha_B \right] H_B^0 \bar{t}_{i+3} P_L t_{j+3} \\
& + \left[\lambda_u (U_t^\dagger)_{i2} (W_t)_{2j} \sin \alpha_B + \lambda_Q (U_t^\dagger)_{i2} (W_t)_{2j} \cos \alpha_B \right] H_B^0 \bar{t}_{i+3} P_R t_{j+3} \} \\
& - \frac{i}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[\lambda_u (W_t^\dagger)_{i2} (U_t)_{2j} \cos \beta_B - \lambda_Q (W_t^\dagger)_{i1} (U_t)_{1j} \sin \beta_B \right] A_B^0 \bar{t}_{i+3} P_L t_{j+3} \right. \\
& - \left[\lambda_u (U_t^\dagger)_{i2} (W_t)_{2j} \cos \beta_B - \lambda_Q (U_t^\dagger)_{i2} (W_t)_{2j} \sin \beta_B \right] A_B^0 \bar{t}_{i+3} P_R t_{j+3} \\
& + \left[\lambda_u (W_t^\dagger)_{i2} (U_t)_{2j} \sin \beta_B + \lambda_Q (W_t^\dagger)_{i1} (U_t)_{1j} \cos \beta_B \right] G_B^0 \bar{t}_{i+3} P_L t_{j+3} \\
& \left. - \left[\lambda_u (U_t^\dagger)_{i2} (W_t)_{2j} \sin \beta_B + \lambda_Q (U_t^\dagger)_{i2} (W_t)_{2j} \cos \beta_B \right] H_B^0 \bar{t}_{i+3} P_R t_{j+3} \right\} \quad (A1)
\end{aligned}$$

Similarly, the couplings between the neutral Higgs and charged $-1/3$ exotic quarks are written as

$$\begin{aligned}
\mathcal{L}_{Hb'b'} &= \frac{1}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[Y_{d_4} (W_b^\dagger)_{i2} (U_b)_{1j} \sin \alpha - Y_{d_5} (W_b^\dagger)_{i1} (U_b)_{2j} \cos \alpha \right] h_B^0 \bar{b}_{i+3} P_L b_{j+3} \right. \\
& + \left[Y_{d_4} (U_b^\dagger)_{i1} (W_b)_{2j} \sin \alpha - Y_{d_5} (U_b^\dagger)_{i2} (W_b)_{1j} \cos \alpha \right] h_B^0 \bar{b}_{i+3} P_R b_{j+3} \\
& - \left[Y_{d_4} (W_b^\dagger)_{i2} (U_b)_{1j} \cos \alpha + Y_{d_5} (W_b^\dagger)_{i1} (U_b)_{2j} \sin \alpha \right] H_B^0 \bar{b}_{i+3} P_L b_{j+3} \\
& - \left[Y_{d_4} (U_b^\dagger)_{i1} (W_b)_{2j} \cos \alpha + Y_{d_5} (U_b^\dagger)_{i2} (W_b)_{1j} \sin \alpha \right] H_B^0 \bar{b}_{i+3} P_R b_{j+3} \\
& + \frac{i}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[Y_{d_4} (W_b^\dagger)_{i2} (U_b)_{1j} \sin \beta - Y_{d_5} (W_b^\dagger)_{i1} (U_b)_{2j} \cos \beta \right] A_B^0 \bar{b}_{i+3} P_L b_{j+3} \right. \\
& - \left[Y_{d_4} (U_b^\dagger)_{i1} (W_b)_{2j} \sin \beta - Y_{d_5} (U_b^\dagger)_{i2} (W_b)_{1j} \cos \beta \right] A_B^0 \bar{b}_{i+3} P_R b_{j+3} \\
& - \left[Y_{d_4} (W_b^\dagger)_{i2} (U_b)_{1j} \cos \beta + Y_{d_5} (W_b^\dagger)_{i1} (U_b)_{2j} \sin \beta \right] G_B^0 \bar{b}_{i+3} P_L b_{j+3} \\
& + \left[Y_{d_4} (U_b^\dagger)_{i1} (W_b)_{2j} \cos \beta + Y_{d_5} (U_b^\dagger)_{i2} (W_b)_{1j} \sin \beta \right] G_B^0 \bar{b}_{i+3} P_R b_{j+3} \\
& - \frac{1}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[\lambda_d (W_b^\dagger)_{i2} (U_b)_{2j} \cos \alpha_B + \lambda_Q (W_b^\dagger)_{i1} (U_b)_{1j} \sin \alpha_B \right] h_B^0 \bar{b}_{i+3} P_L b_{j+3} \right. \\
& + \left[\lambda_d (U_b^\dagger)_{i2} (W_b)_{2j} \cos \alpha_B + \lambda_Q (U_b^\dagger)_{i2} (W_b)_{2j} \sin \alpha_B \right] h_B^0 \bar{b}_{i+3} P_R b_{j+3} \\
& + \left[\lambda_d (W_b^\dagger)_{i2} (U_b)_{2j} \sin \alpha_B + \lambda_Q (W_b^\dagger)_{i1} (U_b)_{1j} \cos \alpha_B \right] H_B^0 \bar{b}_{i+3} P_L b_{j+3} \\
& + \left[\lambda_d (U_b^\dagger)_{i2} (W_b)_{2j} \sin \alpha_B + \lambda_Q (U_b^\dagger)_{i2} (W_b)_{2j} \cos \alpha_B \right] H_B^0 \bar{b}_{i+3} P_R b_{j+3} \} \\
& - \frac{i}{\sqrt{2}} \sum_{i,j=1}^2 \left\{ \left[\lambda_d (W_b^\dagger)_{i2} (U_b)_{2j} \cos \beta_B + \lambda_Q (W_b^\dagger)_{i1} (U_b)_{1j} \sin \beta_B \right] A_B^0 \bar{b}_{i+3} P_L b_{j+3} \right. \\
& - \left[\lambda_d (U_b^\dagger)_{i2} (W_b)_{2j} \cos \beta_B + \lambda_Q (U_b^\dagger)_{i2} (W_b)_{2j} \sin \beta_B \right] A_B^0 \bar{b}_{i+3} P_R b_{j+3} \\
& + \left[\lambda_d (W_b^\dagger)_{i2} (U_b)_{2j} \sin \beta_B + \lambda_Q (W_b^\dagger)_{i1} (U_b)_{1j} \cos \beta_B \right] G_B^0 \bar{b}_{i+3} P_L b_{j+3} \\
& \left. + \left[\lambda_d (U_b^\dagger)_{i2} (W_b)_{2j} \sin \beta_B + \lambda_Q (U_b^\dagger)_{i2} (W_b)_{2j} \cos \beta_B \right] G_B^0 \bar{b}_{i+3} P_R b_{j+3} \right\}
\end{aligned}$$

$$-\left[\lambda_d(U_b^\dagger)_{i2}(W_b)_{2j}\sin\beta_B+\lambda_Q(U_b^\dagger)_{i2}(W_b)_{2j}\cos\beta_B\right]G_B^0\bar{b}_{i+3}P_Rb_{j+3}\Big\} \quad (\text{A2})$$

Appendix B: mass squared matrices for exotic squarks

For charged 2/3 exotic scalar quarks, the elements of mass squared matrix are written as

$$\begin{aligned} \mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_4^{1*}\tilde{Q}_4^1) &= m_{\tilde{Q}_4}^2 + \frac{1}{2}Y_{u_4}^2v_u^2 + \frac{1}{2}Y_{d_4}^2v_d^2 + \frac{1}{2}\lambda_Q^2v_B^2 + \left(\frac{1}{2} - \frac{2}{3}s_w^2\right)m_Z^2\cos 2\beta \\ &\quad + \frac{B_4}{2}m_{Z_B}^2\cos 2\beta_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{U}_4^c\tilde{U}_4^{c*}) &= m_{\tilde{U}_4}^2 + \frac{1}{2}Y_{u_4}^2v_u^2 + \frac{1}{2}\lambda_u^2\bar{v}_B^2 - \frac{2}{3}s_w^2m_Z^2\cos 2\beta - \frac{B_4}{2}m_{Z_B}^2\cos 2\beta_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{2c}\tilde{Q}_5^{2c*}) &= m_{\tilde{Q}_5}^2 + \frac{1}{2}Y_{u_5}^2v_d^2 + \frac{1}{2}Y_{d_5}^2v_u^2 + \frac{1}{2}\lambda_Q^2v_B^2 + \left(\frac{1}{2} - \frac{1}{3}s_w^2\right)m_Z^2\cos 2\beta \\ &\quad - \frac{1+B_4}{2}m_{Z_B}^2\cos 2\beta_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{U}_5^*\tilde{U}_5) &= m_{\tilde{U}_5}^2 + \frac{1}{2}Y_{u_5}^2v_d^2 + \frac{1}{2}\lambda_u^2\bar{v}_B^2 + \frac{2}{3}s_w^2m_Z^2\cos 2\beta + \frac{1+B_4}{2}m_{Z_B}^2\cos 2\beta_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{U}_4^c\tilde{Q}_4^1) &= -\frac{1}{\sqrt{2}}v_uY_{u_4}A_{u_4} + \frac{1}{\sqrt{2}}Y_{u_4}\mu v_d, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{2c}\tilde{Q}_4^1) &= -\frac{1}{\sqrt{2}}v_B\lambda_QA_{BQ} + \sqrt{2}\lambda_Q\mu_B\bar{v}_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{U}_5^*\tilde{Q}_4^1) &= -\frac{1}{\sqrt{2}}Y_{u_4}\lambda_u v_u\bar{v}_B + \frac{1}{\sqrt{2}}Y_{u_5}\lambda_Q v_d v_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{2c}\tilde{U}_4^{c*}) &= \frac{1}{2}\lambda_QY_{u_4}v_u v_B - \frac{1}{2}\lambda_uY_{u_5}v_d\bar{v}_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{U}_5^*\tilde{U}_4^{c*}) &= -\frac{1}{\sqrt{2}}\lambda_uA_{BU}\bar{v}_B + \frac{1}{\sqrt{2}}\lambda_u\mu_B v_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{2c}\tilde{U}_5) &= -\frac{1}{\sqrt{2}}Y_{u_5}A_{u_5}v_d + \frac{1}{\sqrt{2}}Y_{u_5}\mu v_u. \end{aligned} \quad (\text{B1})$$

For charged $-1/3$ exotic scalar quarks, the elements of mass squared matrix are given as

$$\begin{aligned} \mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_4^{2*}\tilde{Q}_4^2) &= m_{\tilde{Q}_4}^2 + \frac{1}{2}Y_{u_4}^2v_u^2 + \frac{1}{2}Y_{d_4}^2v_d^2 + \frac{1}{2}\lambda_Q^2v_B^2 - \left(\frac{1}{2} - \frac{2}{3}s_w^2\right)m_Z^2\cos 2\beta \\ &\quad + \frac{B_4}{2}m_{Z_B}^2\cos 2\beta_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{D}_4^c\tilde{D}_4^{c*}) &= m_{\tilde{D}_4}^2 + \frac{1}{2}Y_{d_4}^2v_d^2 + \frac{1}{2}\lambda_d^2\bar{v}_B^2 - \frac{1}{3}s_w^2m_Z^2\cos 2\beta - \frac{B_4}{2}m_{Z_B}^2\cos 2\beta_B, \\ \mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{1c}\tilde{Q}_5^{1c*}) &= m_{\tilde{Q}_5}^2 + \frac{1}{2}Y_{u_5}^2v_d^2 + \frac{1}{2}Y_{d_5}^2v_u^2 + \frac{1}{2}\lambda_Q^2v_B^2 - \left(\frac{1}{2} + \frac{1}{3}s_w^2\right)m_Z^2\cos 2\beta \end{aligned}$$

$$\begin{aligned}
& -\frac{1+B_4}{2}m_{Z_B}^2 \cos 2\beta_B, \\
\mathcal{M}_{\tilde{t}'}^2(\tilde{D}_5^* \tilde{D}_5) &= m_{\tilde{D}_5}^2 + \frac{1}{2}Y_{d_5}^2 v_u^2 + \frac{1}{2}\lambda_d^2 \bar{v}_B^2 + \frac{1}{3}s_w^2 m_Z^2 \cos 2\beta + \frac{1+B_4}{2}m_{Z_B}^2 \cos 2\beta_B, \\
\mathcal{M}_{\tilde{t}'}^2(\tilde{D}_4^c \tilde{Q}_4^2) &= -\frac{1}{\sqrt{2}}Y_{d_4} v_d A_{d_4} + \frac{1}{\sqrt{2}}Y_{d_4} \mu v_d, \\
\mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{1c} \tilde{Q}_4^2) &= -\frac{1}{\sqrt{2}}\lambda_Q v_B A_{BQ} + \sqrt{2}\lambda_Q \mu_B \bar{v}_B, \\
\mathcal{M}_{\tilde{t}'}^2(\tilde{D}_5^* \tilde{Q}_4^2) &= -\frac{1}{\sqrt{2}}Y_{d_4} \lambda_d v_d \bar{v}_B + \frac{1}{\sqrt{2}}Y_{d_5} \lambda_Q v_u v_B, \\
\mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{1c} \tilde{D}_4^{c*}) &= \frac{1}{2}\lambda_Q Y_{d_4} v_d v_B + \frac{1}{2}\lambda_d Y_{d_5} v_u \bar{v}_B, \\
\mathcal{M}_{\tilde{t}'}^2(\tilde{D}_5^* \tilde{D}_4^{c*}) &= -\frac{1}{\sqrt{2}}\lambda_d A_{BD} \bar{v}_B + \frac{1}{\sqrt{2}}\lambda_d \mu_B v_B, \\
\mathcal{M}_{\tilde{t}'}^2(\tilde{Q}_5^{1c} \tilde{D}_5) &= -\frac{1}{\sqrt{2}}Y_{d_5} A_{d_5} v_u + \frac{1}{\sqrt{2}}Y_{d_5} \mu v_d. \tag{B2}
\end{aligned}$$

Appendix C: The couplings between neutral Higgs and exotic squarks

In the mass basis, the couplings between the neutral Higgs and exotic squarks are

$$\begin{aligned}
\mathcal{L}_{H\tilde{u}_i^* \tilde{u}_j} &= \sum_{i,j}^4 \left\{ \left[\xi_{uij}^S \cos \alpha - \xi_{dij}^S \sin \alpha \right] h^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + \left[\eta_{uij}^S \cos \alpha - \eta_{dij}^S \sin \alpha \right] h^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \right. \\
&+ \left[\xi_{uij}^S \sin \alpha + \xi_{dij}^S \cos \alpha \right] H^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + \left[\eta_{uij}^S \sin \alpha + \eta_{dij}^S \cos \alpha \right] H^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \\
&+ i \left[\xi_{uij}^P \cos \beta - \xi_{dij}^P \sin \beta \right] A^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + i \left[\eta_{uij}^P \cos \beta - \eta_{dij}^P \sin \beta \right] A^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \\
&+ i \left[\xi_{uij}^P \sin \beta + \xi_{dij}^P \cos \beta \right] G^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + i \left[\eta_{uij}^P \sin \beta + \eta_{dij}^P \cos \beta \right] G^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \\
&+ \left[\zeta_{uij}^S \cos \alpha_B - \zeta_{dij}^S \sin \alpha_B \right] h_B^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + \left[\zeta_{uij}^S \cos \alpha_B - \zeta_{dij}^S \sin \alpha_B \right] h_B^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \\
&+ \left[\zeta_{uij}^S \sin \alpha_B + \zeta_{dij}^S \cos \alpha_B \right] H_B^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + \left[\zeta_{uij}^S \sin \alpha_B + \zeta_{dij}^S \cos \alpha_B \right] H_B^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \\
&+ i \left[\zeta_{uij}^P \cos \beta_B - \zeta_{dij}^P \sin \beta_B \right] A_B^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + i \left[\zeta_{uij}^P \cos \beta_B - \zeta_{dij}^P \sin \beta_B \right] A_B^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \\
&+ i \left[\zeta_{uij}^P \sin \beta_B + \zeta_{dij}^P \cos \beta_B \right] G_B^0 \tilde{\mathcal{U}}_i^* \tilde{\mathcal{U}}_j + i \left[\zeta_{uij}^P \sin \beta_B + \zeta_{dij}^P \cos \beta_B \right] G_B^0 \tilde{\mathcal{D}}_i^* \tilde{\mathcal{D}}_j \left. \right\} \tag{C1}
\end{aligned}$$

with

$$\begin{aligned}
\xi_{uij}^S &= \frac{1}{\sqrt{2}}Y_{u_5} \mu (U_{i3}^\dagger U_{4j} + U_{i4}^\dagger U_{3j}) + \frac{1}{2}\lambda_Q Y_{u_4} v_B (U_{i3}^\dagger U_{2j} + U_{i2}^\dagger U_{3j}) \\
&- \frac{1}{2}\lambda_u Y_{u_4} \bar{v}_B (U_{i1}^\dagger U_{4j} + U_{i4}^\dagger U_{1j}) + \frac{e^2}{4s_w^2} v_u (U_{i3}^\dagger U_{3j} - U_{i1}^\dagger U_{1j})
\end{aligned}$$

$$\begin{aligned}
& + \frac{e^2}{12c_W^2} v_u \left(U_{i1}^\dagger U_{1j} - U_{i3}^\dagger U_{3j} - 4U_{i2}^\dagger U_{2j} + 4U_{i4}^\dagger U_{4j} \right) \\
& - \frac{1}{\sqrt{2}} A_{u_4} Y_{u_4} \left(U_{i2}^\dagger U_{1j} + U_{i1}^\dagger U_{2j} \right), \\
\xi_{dij}^S &= \frac{1}{\sqrt{2}} Y_{u_4} \mu \left(U_{i2}^\dagger U_{1j} + U_{i1}^\dagger U_{2j} \right) + \frac{1}{2} \lambda_Q Y_{u_5} v_B \left(U_{i5}^\dagger U_{1j} + U_{i1}^\dagger U_{5j} \right) \\
& - \frac{1}{2} \lambda_u Y_{u_5} \bar{v}_B \left(U_{i2}^\dagger U_{3j} + U_{i3}^\dagger U_{2j} \right) - \frac{e^2}{4s_W^2} v_d \left(U_{i3}^\dagger U_{3j} + U_{i1}^\dagger U_{1j} \right) \\
& - \frac{e^2}{12c_W^2} v_d \left(U_{i1}^\dagger U_{1j} - U_{i3}^\dagger U_{3j} - 4U_{i2}^\dagger U_{2j} + 4U_{i4}^\dagger U_{4j} \right) \\
& - \frac{1}{\sqrt{2}} A_{u_5} Y_{u_5} \left(U_{i3}^\dagger U_{4j} + U_{i4}^\dagger U_{3j} \right), \\
\eta_{uij}^S &= \frac{1}{\sqrt{2}} Y_{d_4} \mu \left(D_{i2}^\dagger D_{1j} + D_{i1}^\dagger D_{2j} \right) + \frac{1}{2} \lambda_Q Y_{d_5} v_B \left(D_{i4}^\dagger D_{1j} + D_{i1}^\dagger D_{4j} \right) \\
& - \frac{1}{2} \lambda_d Y_{d_5} \bar{v}_B \left(D_{i2}^\dagger D_{3j} + D_{i3}^\dagger D_{2j} \right) + \frac{e^2}{4s_W^2} v_u \left(D_{i1}^\dagger D_{1j} - D_{i3}^\dagger D_{3j} \right) \\
& + \frac{e^2}{12c_W^2} v_u \left(D_{i1}^\dagger D_{1j} - D_{i3}^\dagger D_{3j} + 2D_{i2}^\dagger D_{2j} - 2D_{i4}^\dagger D_{4j} \right) \\
& - \frac{1}{\sqrt{2}} A_{d_5} Y_{d_5} \left(D_{i3}^\dagger D_{4j} + D_{i4}^\dagger D_{3j} \right), \\
\eta_{dij}^S &= \frac{1}{\sqrt{2}} Y_{d_5} \mu \left(D_{i3}^\dagger D_{4j} + D_{i4}^\dagger D_{3j} \right) + \frac{1}{2} \lambda_Q Y_{d_4} v_B \left(D_{i3}^\dagger D_{2j} + D_{i2}^\dagger D_{3j} \right) \\
& - \frac{1}{2} \lambda_d Y_{d_4} \bar{v}_B \left(D_{i1}^\dagger D_{4j} + D_{i4}^\dagger D_{1j} \right) - \frac{e^2}{4s_W^2} v_d \left(D_{i1}^\dagger D_{1j} - D_{i3}^\dagger D_{3j} \right) \\
& - \frac{e^2}{12c_W^2} v_u \left(D_{i1}^\dagger D_{1j} - D_{i3}^\dagger D_{3j} + 2D_{i2}^\dagger D_{2j} - 2D_{i4}^\dagger D_{4j} \right) \\
& - \frac{1}{\sqrt{2}} A_{d_4} Y_{d_4} \left(D_{i2}^\dagger D_{1j} + D_{i1}^\dagger D_{2j} \right), \\
\xi_{uij}^P &= \frac{1}{\sqrt{2}} Y_{u_5} \mu \left(U_{i3}^\dagger U_{4j} - U_{i4}^\dagger U_{3j} \right) - \frac{1}{2} \lambda_Q Y_{u_4} v_B \left(U_{i3}^\dagger U_{2j} - U_{i2}^\dagger U_{3j} \right) \\
& + \frac{1}{2} \lambda_u Y_{u_4} \bar{v}_B \left(U_{i1}^\dagger U_{4j} - U_{i4}^\dagger U_{1j} \right) - \frac{1}{\sqrt{2}} A_{u_4} Y_{u_4} \left(U_{i2}^\dagger U_{1j} - U_{i1}^\dagger U_{2j} \right), \\
\xi_{dij}^P &= \frac{1}{\sqrt{2}} Y_{u_4} \mu \left(U_{i2}^\dagger U_{1j} - U_{i1}^\dagger U_{2j} \right) - \frac{1}{2} \lambda_Q Y_{u_5} v_B \left(U_{i5}^\dagger U_{1j} - U_{i1}^\dagger U_{5j} \right) \\
& + \frac{1}{2} \lambda_u Y_{u_5} \bar{v}_B \left(U_{i2}^\dagger U_{3j} - U_{i3}^\dagger U_{2j} \right) - \frac{1}{\sqrt{2}} A_{u_5} Y_{u_5} \left(U_{i3}^\dagger U_{4j} - U_{i4}^\dagger U_{3j} \right), \\
\eta_{uij}^P &= \frac{1}{\sqrt{2}} Y_{d_4} \mu \left(D_{i2}^\dagger D_{1j} - D_{i1}^\dagger D_{2j} \right) - \frac{1}{2} \lambda_Q Y_{d_5} v_B \left(D_{i4}^\dagger D_{1j} - D_{i1}^\dagger D_{4j} \right)
\end{aligned}$$

$$\begin{aligned}
& +\frac{1}{2}\lambda_d Y_{d_5} \bar{v}_B (D_{i2}^\dagger D_{3j} - D_{i3}^\dagger D_{2j}) - \frac{1}{\sqrt{2}} A_{d_5} Y_{d_5} (D_{i3}^\dagger D_{4j} - D_{i4}^\dagger D_{3j}) , \\
\eta_{dij}^P &= \frac{1}{\sqrt{2}} Y_{d_5} \mu (D_{i3}^\dagger D_{4j} - D_{i4}^\dagger D_{3j}) - \frac{1}{2} \lambda_Q Y_{d_4} v_B (D_{i3}^\dagger D_{2j} - D_{i2}^\dagger D_{3j}) \\
& +\frac{1}{2} \lambda_d Y_{d_4} \bar{v}_B (D_{i1}^\dagger D_{4j} - D_{i4}^\dagger D_{1j}) - \frac{1}{\sqrt{2}} A_{d_4} Y_{d_4} (D_{i2}^\dagger D_{1j} - D_{i1}^\dagger D_{2j}) , \\
\zeta_{uij}^S &= \frac{1}{\sqrt{2}} \lambda_u \mu_B (U_{i2}^\dagger U_{4j} + U_{i4}^\dagger U_{2j}) + \frac{1}{2} \lambda_Q Y_{u_4} v_u (U_{i3}^\dagger U_{2j} + U_{i2}^\dagger U_{3j}) \\
& -\frac{1}{2} \lambda_Q Y_{u_5} v_d (U_{i4}^\dagger U_{1j} + U_{i1}^\dagger U_{4j}) + g_B^2 v_B (B_4 U_{i1}^\dagger U_{1j} - (1+B_4) U_{i3}^\dagger U_{3j} \\
& -B_4 U_{i2}^\dagger U_{2j} + (1+B_4) U_{i4}^\dagger U_{4j}) - \frac{1}{\sqrt{2}} A_{BQ} \lambda_Q (U_{i3}^\dagger U_{1j} + U_{i1}^\dagger U_{3j}) , \\
\zeta_{dij}^S &= \frac{1}{\sqrt{2}} \lambda_Q \mu_B (U_{i3}^\dagger U_{1j} + U_{i1}^\dagger U_{3j}) - \frac{1}{2} \lambda_u Y_{u_4} v_u (U_{i1}^\dagger U_{4j} + U_{i4}^\dagger U_{1j}) \\
& -\frac{1}{2} \lambda_u Y_{u_5} v_d (U_{i2}^\dagger U_{3j} + U_{i3}^\dagger U_{2j}) - g_B^2 \bar{v}_B (B_4 U_{i1}^\dagger U_{1j} - (1+B_4) U_{i3}^\dagger U_{3j} \\
& -B_4 U_{i2}^\dagger U_{2j} + (1+B_4) U_{i4}^\dagger U_{4j}) + \frac{1}{\sqrt{2}} A_{BU} \lambda_u (U_{i2}^\dagger U_{4j} + U_{i4}^\dagger U_{2j}) , \\
\zeta_{uij}^S &= \frac{1}{\sqrt{2}} \lambda_d \mu_B (D_{i2}^\dagger D_{4j} + D_{i4}^\dagger D_{2j}) + \frac{1}{2} \lambda_Q Y_{d_4} v_d (D_{i3}^\dagger D_{2j} + D_{i2}^\dagger D_{3j}) \\
& -\frac{1}{2} \lambda_Q Y_{d_5} v_u (D_{i4}^\dagger D_{1j} + D_{i1}^\dagger D_{4j}) + g_B^2 v_B (B_4 D_{i1}^\dagger D_{1j} - (1+B_4) D_{i3}^\dagger D_{3j} \\
& -B_4 D_{i2}^\dagger D_{2j} + (1+B_4) D_{i4}^\dagger D_{4j}) - \frac{1}{\sqrt{2}} A_{BQ} \lambda_Q (D_{i3}^\dagger D_{1j} + D_{i1}^\dagger D_{3j}) , \\
\zeta_{dij}^S &= -\frac{1}{\sqrt{2}} \lambda_Q \mu_B (D_{i3}^\dagger D_{1j} + D_{i1}^\dagger D_{3j}) - \frac{1}{2} \lambda_d Y_{d_4} v_d (D_{i1}^\dagger D_{4j} + D_{i4}^\dagger D_{1j}) \\
& -\frac{1}{2} \lambda_d Y_{d_5} v_u (D_{i2}^\dagger D_{3j} + D_{i3}^\dagger D_{2j}) - g_B^2 \bar{v}_B (B_4 D_{i1}^\dagger D_{1j} - (1+B_4) D_{i3}^\dagger D_{3j} \\
& -B_4 D_{i2}^\dagger D_{2j} + (1+B_4) D_{i4}^\dagger D_{4j}) + \frac{1}{\sqrt{2}} A_{BD} \lambda_d (D_{i2}^\dagger D_{4j} + D_{i4}^\dagger D_{2j}) , \\
\zeta_{uij}^P &= \frac{1}{\sqrt{2}} \lambda_u \mu_B (U_{i2}^\dagger U_{4j} - U_{i4}^\dagger U_{2j}) + \frac{1}{2} \lambda_Q Y_{u_4} v_u (U_{i3}^\dagger U_{2j} - U_{i2}^\dagger U_{3j}) \\
& -\frac{1}{2} \lambda_Q Y_{u_5} v_d (U_{i4}^\dagger U_{1j} - U_{i1}^\dagger U_{4j}) - \frac{1}{\sqrt{2}} A_{BQ} \lambda_Q (U_{i3}^\dagger U_{1j} - U_{i1}^\dagger U_{3j}) , \\
\zeta_{dij}^P &= \frac{1}{\sqrt{2}} \lambda_Q \mu_B (U_{i3}^\dagger U_{1j} - U_{i1}^\dagger U_{3j}) - \frac{1}{2} \lambda_u Y_{u_4} v_u (U_{i1}^\dagger U_{4j} - U_{i4}^\dagger U_{1j}) \\
& -\frac{1}{2} \lambda_u Y_{u_5} v_d (U_{i2}^\dagger U_{3j} - U_{i3}^\dagger U_{2j}) + \frac{1}{\sqrt{2}} A_{BU} \lambda_u (U_{i2}^\dagger U_{4j} - U_{i4}^\dagger U_{2j}) , \\
\zeta_{uij}^P &= \frac{1}{\sqrt{2}} \lambda_d \mu_B (D_{i2}^\dagger D_{4j} - D_{i4}^\dagger D_{2j}) + \frac{1}{2} \lambda_Q Y_{d_4} v_d (D_{i3}^\dagger D_{2j} - D_{i2}^\dagger D_{3j})
\end{aligned}$$

$$\begin{aligned}
& -\frac{1}{2}\lambda_Q Y_{d_5} v_u (D_{i4}^\dagger D_{1j} - D_{i1}^\dagger D_{4j}) - \frac{1}{\sqrt{2}} A_{BQ} \lambda_Q (D_{i3}^\dagger D_{1j} - D_{i1}^\dagger D_{3j}) , \\
\zeta_{dij}^P = & -\frac{1}{\sqrt{2}} \lambda_Q \mu_B (D_{i3}^\dagger D_{1j} - D_{i1}^\dagger D_{3j}) - \frac{1}{2} \lambda_d Y_{d_4} v_d (D_{i1}^\dagger D_{4j} - D_{i4}^\dagger D_{1j}) \\
& -\frac{1}{2} \lambda_d Y_{d_5} v_u (D_{i2}^\dagger D_{3j} - D_{i3}^\dagger D_{2j}) + \frac{1}{\sqrt{2}} A_{BD} \lambda_d (D_{i2}^\dagger D_{4j} - D_{i4}^\dagger D_{2j}) . \tag{C2}
\end{aligned}$$

Appendix D: The radiative corrections to the mass squared matrix from exotic lepton fields

$$\begin{aligned}
\Delta_{11}^L = & \frac{G_F m_{\nu_4}^4}{\sqrt{2} \pi^2 \sin^2 \beta} \cdot \frac{\mu^2 (A_{\nu_4} - \mu \cot \beta)^2}{(m_{\tilde{\nu}_4^1}^2 - m_{\tilde{\nu}_4^2}^2)^2} g(m_{\tilde{\nu}_4^1}, m_{\tilde{\nu}_4^2}) \\
& + \frac{G_F m_{e_4}^4}{\sqrt{2} \pi^2 \cos^2 \beta} \left\{ \ln \frac{m_{\tilde{e}_4^1} m_{\tilde{e}_4^2}}{m_{e_4}^2} + \frac{A_{e_4} (A_{e_4} - \mu \tan \beta)}{m_{\tilde{e}_4^1}^2 - m_{\tilde{e}_4^2}^2} \ln \frac{m_{\tilde{e}_4^1}^2}{m_{\tilde{e}_4^2}^2} \right. \\
& \left. + \frac{A_{e_4}^2 (A_{e_4} - \mu \tan \beta)^2}{(m_{\tilde{e}_4^1}^2 - m_{\tilde{e}_4^2}^2)^2} g(m_{\tilde{e}_4^1}, m_{\tilde{e}_4^2}) \right\} \\
& + \frac{G_F m_{\nu_5}^4}{\sqrt{2} \pi^2 \cos^2 \beta} \left\{ \ln \frac{m_{\tilde{\nu}_5^1} m_{\tilde{\nu}_5^2}}{m_{\nu_5}^2} + \frac{A_{\nu_5} (A_{\nu_5} - \mu \tan \beta)}{m_{\tilde{\nu}_5^1}^2 - m_{\tilde{\nu}_5^2}^2} \ln \frac{m_{\tilde{\nu}_5^1}^2}{m_{\tilde{\nu}_5^2}^2} \right. \\
& \left. + \frac{A_{\nu_5}^2 (A_{\nu_5} - \mu \tan \beta)^2}{(m_{\tilde{\nu}_5^1}^2 - m_{\tilde{\nu}_5^2}^2)^2} g(m_{\tilde{\nu}_5^1}, m_{\tilde{\nu}_5^2}) \right\} \\
& + \frac{G_F m_{e_5}^4}{\sqrt{2} \pi^2 \sin^2 \beta} \cdot \frac{\mu^2 (A_{e_5} - \mu \cot \beta)^2}{(m_{\tilde{e}_5^1}^2 - m_{\tilde{e}_5^2}^2)^2} g(m_{\tilde{e}_5^1}, m_{\tilde{e}_5^2}) , \\
\Delta_{12}^L = & \frac{G_F m_{\nu_4}^4}{2\sqrt{2} \pi^2 \sin^2 \beta} \cdot \frac{\mu (-A_{\nu_4} + \mu \cot \beta)}{m_{\tilde{\nu}_4^1}^2 - m_{\tilde{\nu}_4^2}^2} \left\{ \ln \frac{m_{\tilde{\nu}_4^1}}{m_{\tilde{\nu}_4^2}} + \frac{A_{\nu_4} (A_{\nu_4} - \mu \cot \beta)}{m_{\tilde{\nu}_4^1}^2 - m_{\tilde{\nu}_4^2}^2} g(m_{\tilde{\nu}_4^1}, m_{\tilde{\nu}_4^2}) \right\} \\
& + \frac{G_F m_{e_4}^4}{2\sqrt{2} \pi^2 \cos^2 \beta} \cdot \frac{\mu (-A_{e_4} + \mu \tan \beta)}{m_{\tilde{e}_4^1}^2 - m_{\tilde{e}_4^2}^2} \left\{ \ln \frac{m_{\tilde{e}_4^1}}{m_{\tilde{e}_4^2}} + \frac{A_{e_4} (A_{e_4} - \mu \tan \beta)}{m_{\tilde{e}_4^1}^2 - m_{\tilde{e}_4^2}^2} g(m_{\tilde{e}_4^1}, m_{\tilde{e}_4^2}) \right\} \\
& + \frac{G_F m_{\nu_5}^4}{2\sqrt{2} \pi^2 \cos^2 \beta} \cdot \frac{\mu (-A_{\nu_5} + \mu \tan \beta)}{m_{\tilde{\nu}_5^1}^2 - m_{\tilde{\nu}_5^2}^2} \left\{ \ln \frac{m_{\tilde{\nu}_5^1}}{m_{\tilde{\nu}_5^2}} + \frac{A_{\nu_5} (A_{\nu_5} - \mu \tan \beta)}{m_{\tilde{\nu}_5^1}^2 - m_{\tilde{\nu}_5^2}^2} g(m_{\tilde{\nu}_5^1}, m_{\tilde{\nu}_5^2}) \right\} \\
& + \frac{G_F m_{e_5}^4}{2\sqrt{2} \pi^2 \sin^2 \beta} \cdot \frac{\mu (-A_{e_5} + \mu \cot \beta)}{m_{\tilde{e}_5^1}^2 - m_{\tilde{e}_5^2}^2} \left\{ \ln \frac{m_{\tilde{e}_5^1}}{m_{\tilde{e}_5^2}} + \frac{A_{e_5} (A_{e_5} - \mu \cot \beta)}{m_{\tilde{e}_5^1}^2 - m_{\tilde{e}_5^2}^2} g(m_{\tilde{e}_5^1}, m_{\tilde{e}_5^2}) \right\} ,
\end{aligned}$$

$$\begin{aligned}
\Delta_{22}^L = & \frac{G_F m_{\nu_4}^4}{\sqrt{2}\pi^2 \sin^2 \beta} \left\{ \ln \frac{m_{\bar{\nu}_4^1} m_{\bar{\nu}_4^2}}{m_{\nu_4}^2} + \frac{A_{\nu_4} (A_{\nu_4} - \mu \cot \beta)}{m_{\bar{\nu}_4^1}^2 - m_{\bar{\nu}_4^2}^2} \ln \frac{m_{\bar{\nu}_4^1}^2}{m_{\bar{\nu}_4^2}^2} \right. \\
& + \frac{A_{\nu_4}^2 (A_{\nu_4} - \mu \cot \beta)^2}{(m_{\bar{\nu}_4^1}^2 - m_{\bar{\nu}_4^2}^2)^2} g(m_{\bar{\nu}_4^1}, m_{\bar{\nu}_4^2}) \left. \right\} \\
& + \frac{G_F m_{e_4}^4}{\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu^2 (A_{e_4} - \mu \tan \beta)^2}{(m_{\bar{e}_4^1}^2 - m_{\bar{e}_4^2}^2)^2} g(m_{\bar{e}_4^1}, m_{\bar{e}_4^2}) \\
& + \frac{G_F m_{\nu_5}^4}{\sqrt{2}\pi^2 \cos^2 \beta} \cdot \frac{\mu^2 (A_{\nu_5} - \mu \tan \beta)^2}{(m_{\bar{\nu}_5^1}^2 - m_{\bar{\nu}_5^2}^2)^2} g(m_{\bar{\nu}_5^1}, m_{\bar{\nu}_5^2}) \\
& + \frac{G_F m_{e_5}^4}{\sqrt{2}\pi^2 \sin^2 \beta} \left\{ \ln \frac{m_{\bar{e}_5^1} m_{\bar{e}_5^2}}{m_{e_5}^2} + \frac{A_{e_5} (A_{e_5} - \mu \cot \beta)}{m_{\bar{e}_5^1}^2 - m_{\bar{e}_5^2}^2} \ln \frac{m_{\bar{e}_5^1}^2}{m_{\bar{e}_5^2}^2} \right. \\
& + \frac{A_{e_5}^2 (A_{e_5} - \mu \cot \beta)^2}{(m_{\bar{e}_5^1}^2 - m_{\bar{e}_5^2}^2)^2} g(m_{\bar{e}_5^1}, m_{\bar{e}_5^2}) \left. \right\} , \tag{D1}
\end{aligned}$$

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